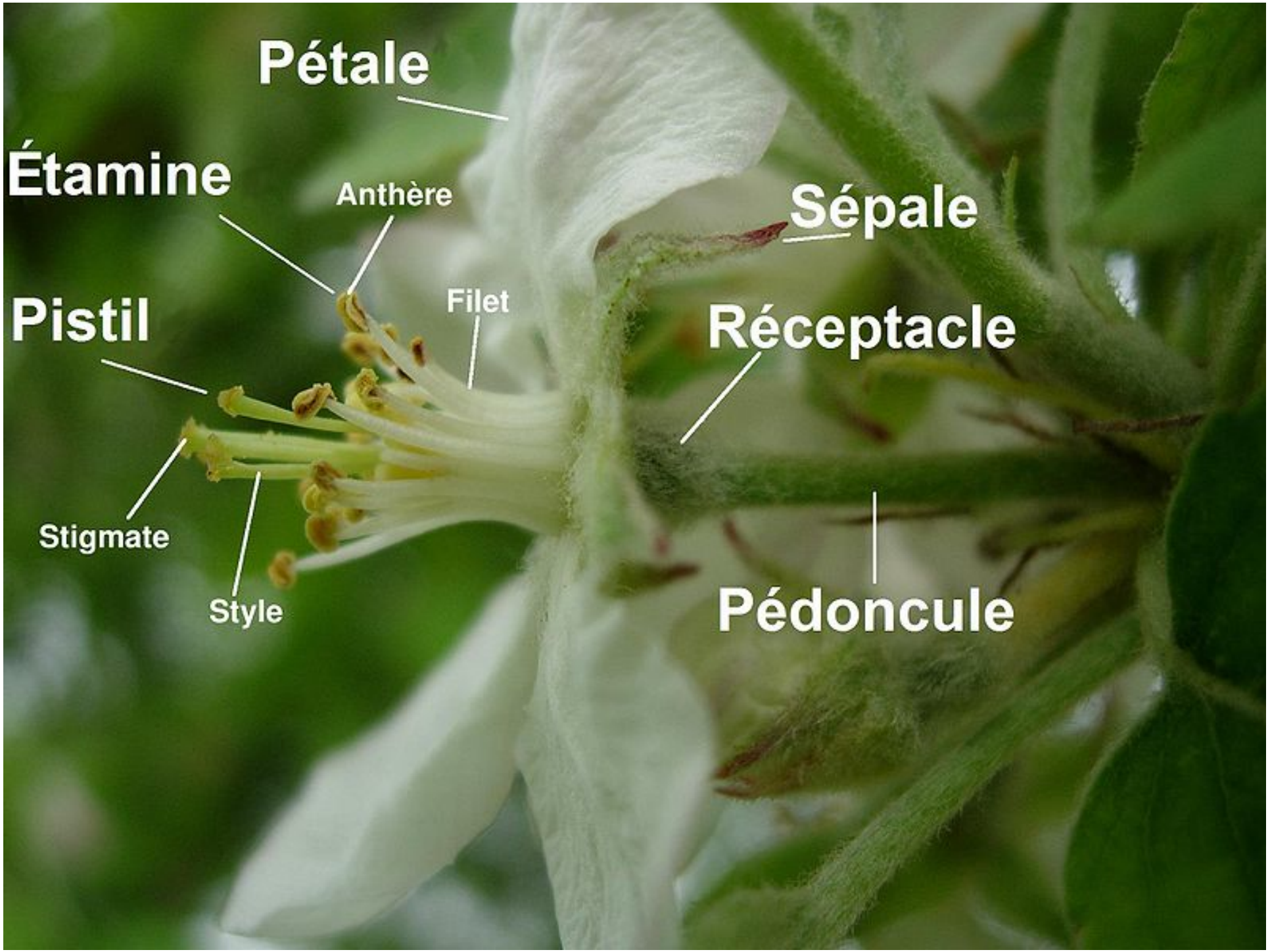
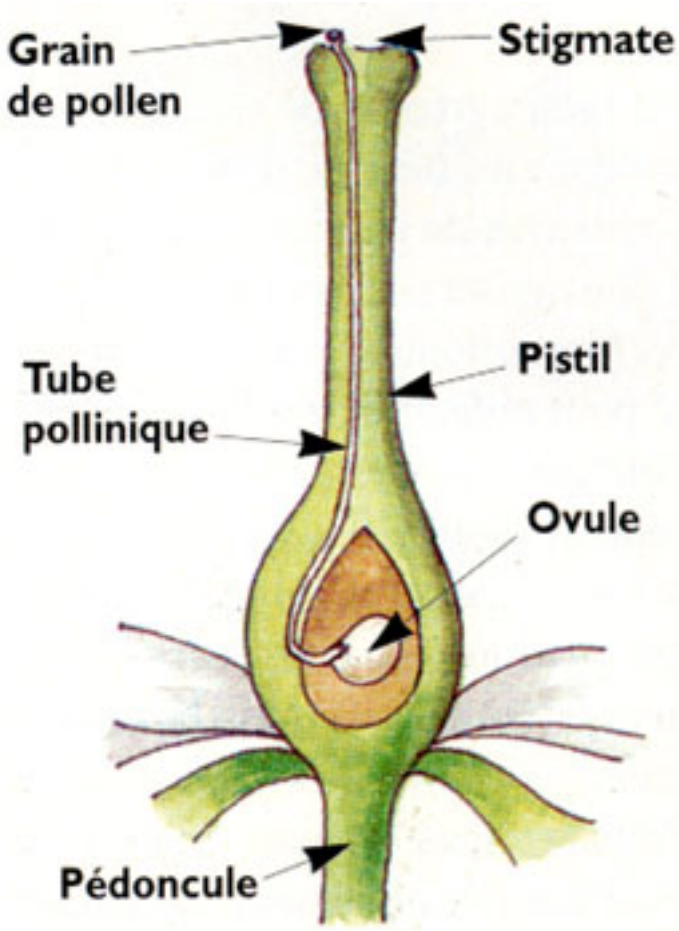
Le code secret des fleurs

Christophe Godin
Inria

Observons la structure d'une fleur (virtuelle !)


Pétale
Étamine
Anthère
Sépale
Filet
Pistil
Réceptacle
Stigmate
Style
Pédoncule

Sa fonction

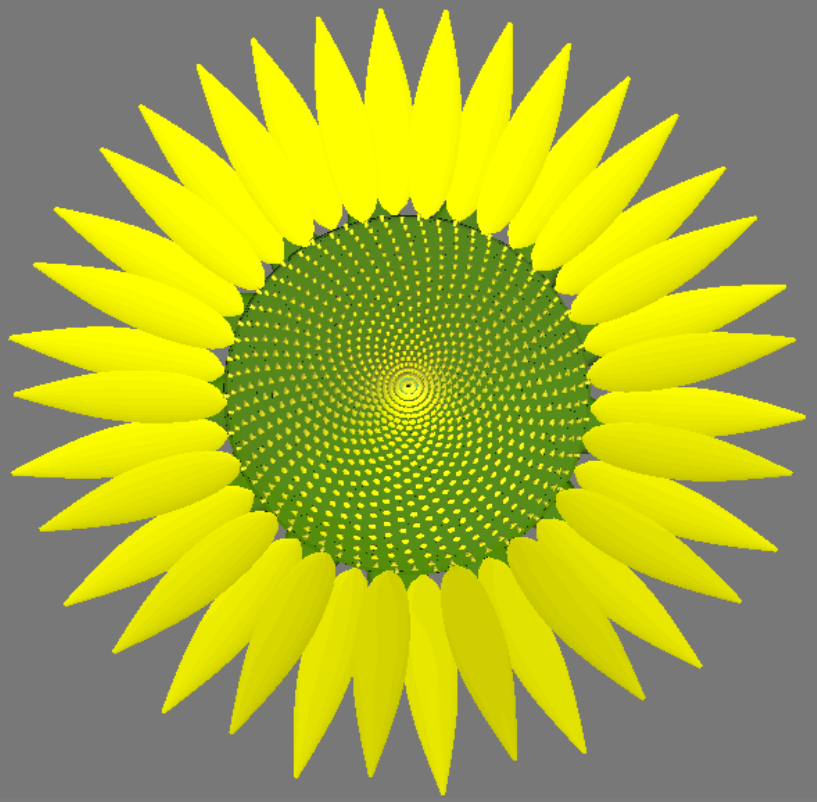

Grain
de pollen
Stigmate
Pistil
Tube
pollinique
Ovule
Pédoncule

Goethe et le concept de metamorphose (1790)

J. W. Goethe (1749-1832)

“Les organes d’une plante correspondent à des transformations d’un unique organe sous-jacent”

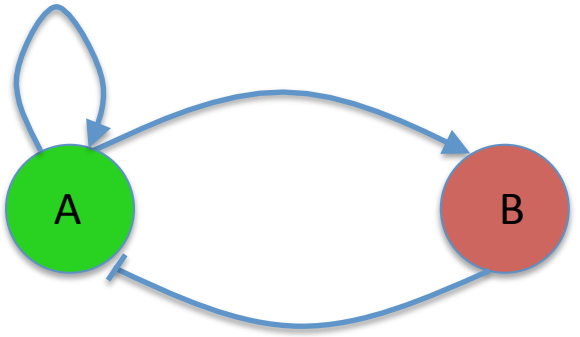
Des structures très différentes, et pourtant !



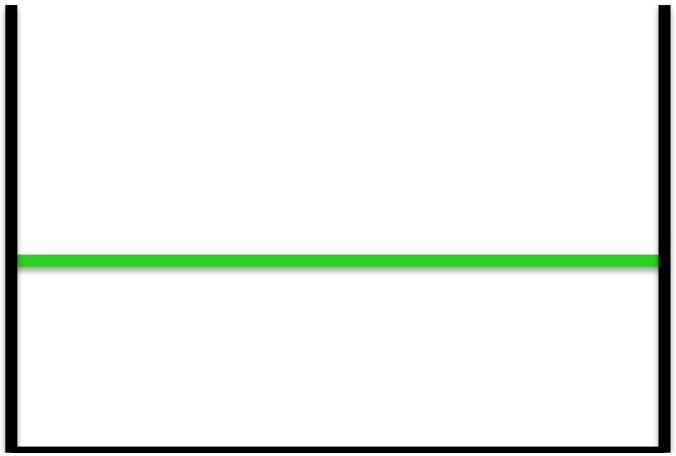
Le code secret des fleurs:
A B C

1952: une découverte surprenante …

Alan Turing

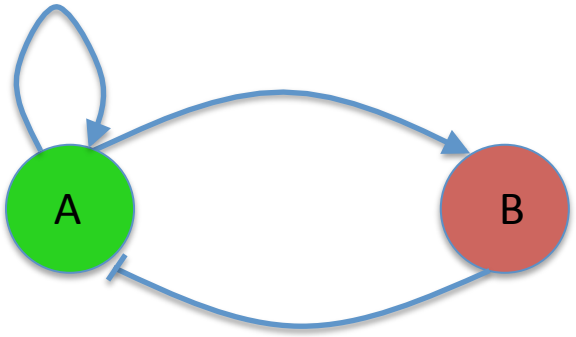


- A est fabriqué un peu partout
- B s'étale plus vite que A

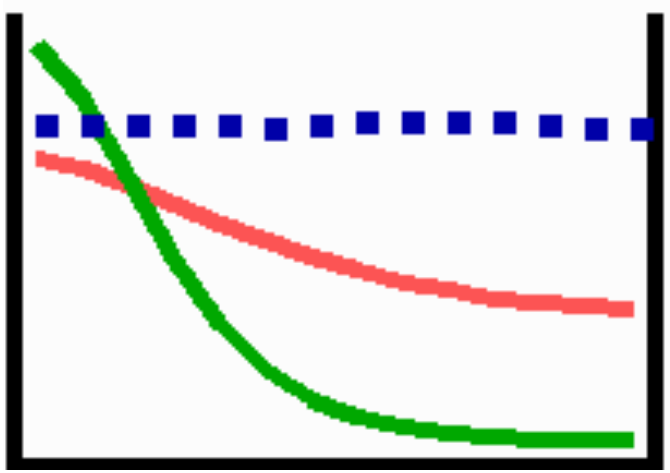


Une découverte surprenante …

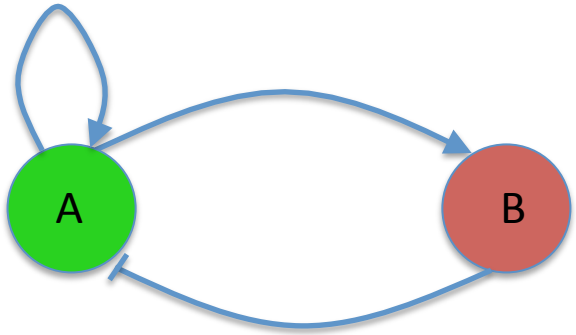
Alan Turing



- A est fabriqué partout
- B s'étale plus vite que A



Ecriture mathématique

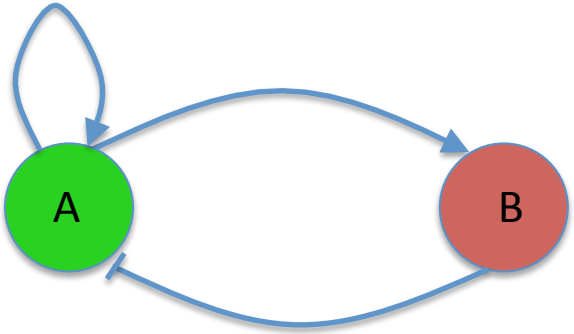


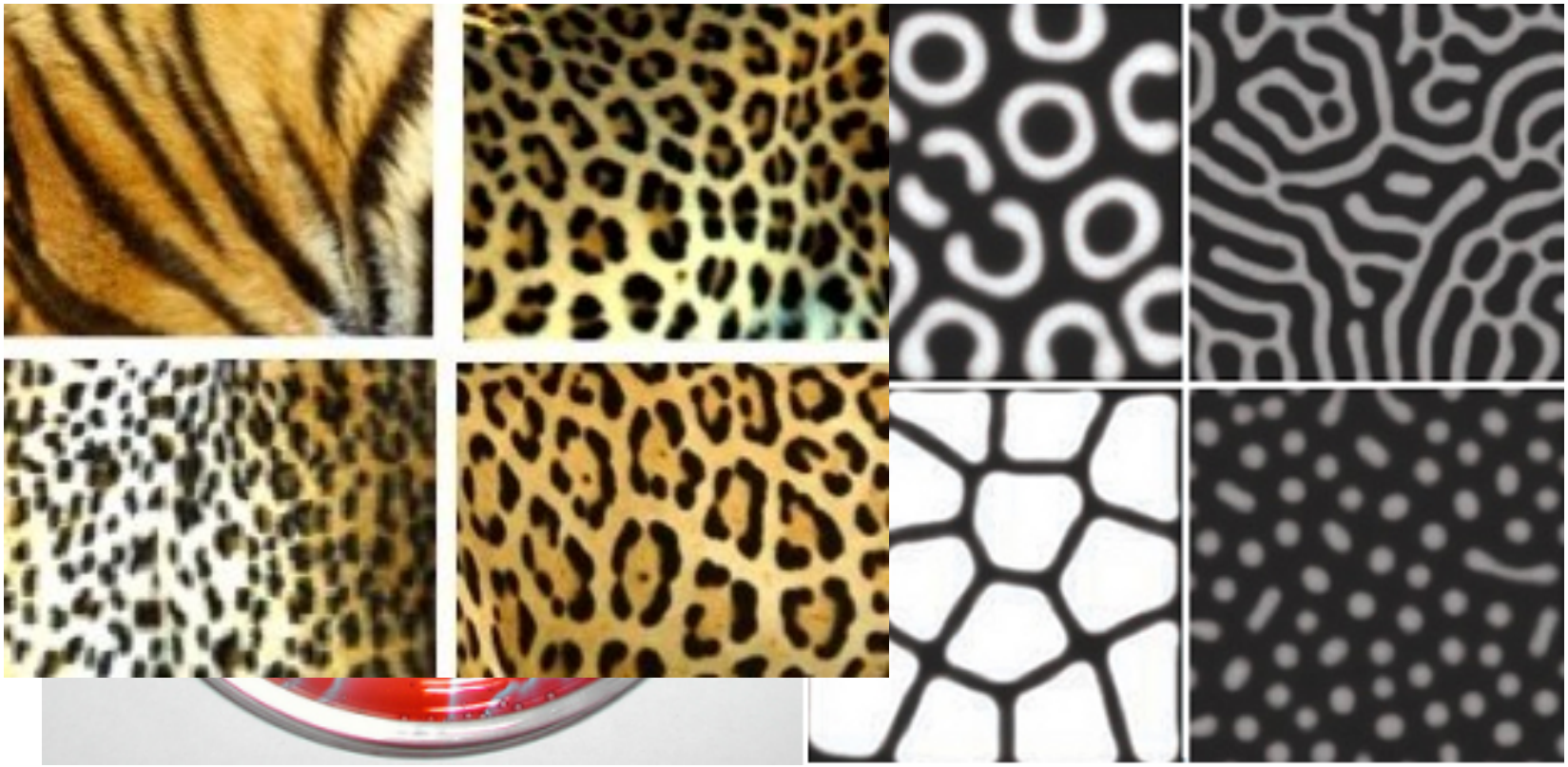
B s'étale plus vite que A

$$\frac{dA}{dt} = c - bA + \frac{A^2}{k(1+dA^2)} + D_A \Delta A$$

$$\frac{dB}{dt} = A^2 - B + D_B \Delta B$$

Il apparaît des formes !

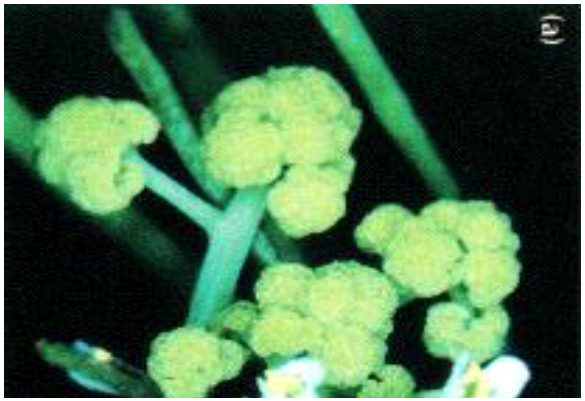


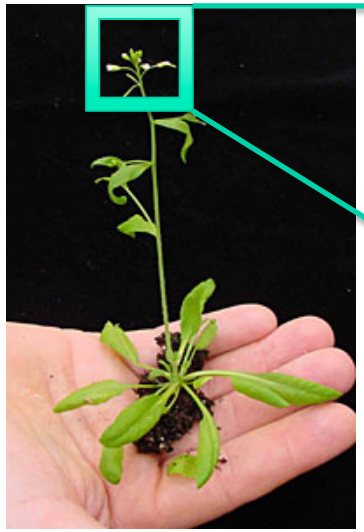


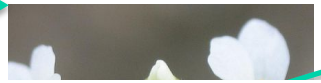
Conjecture de Turing

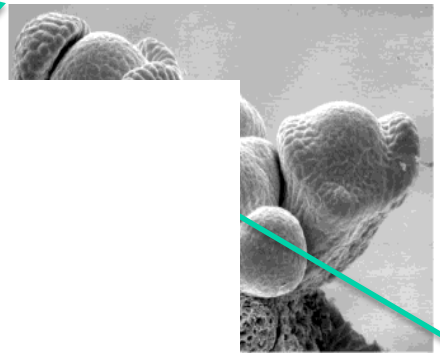
“un tel système pourrait expliquer l’organisation des organes d’une plante !”

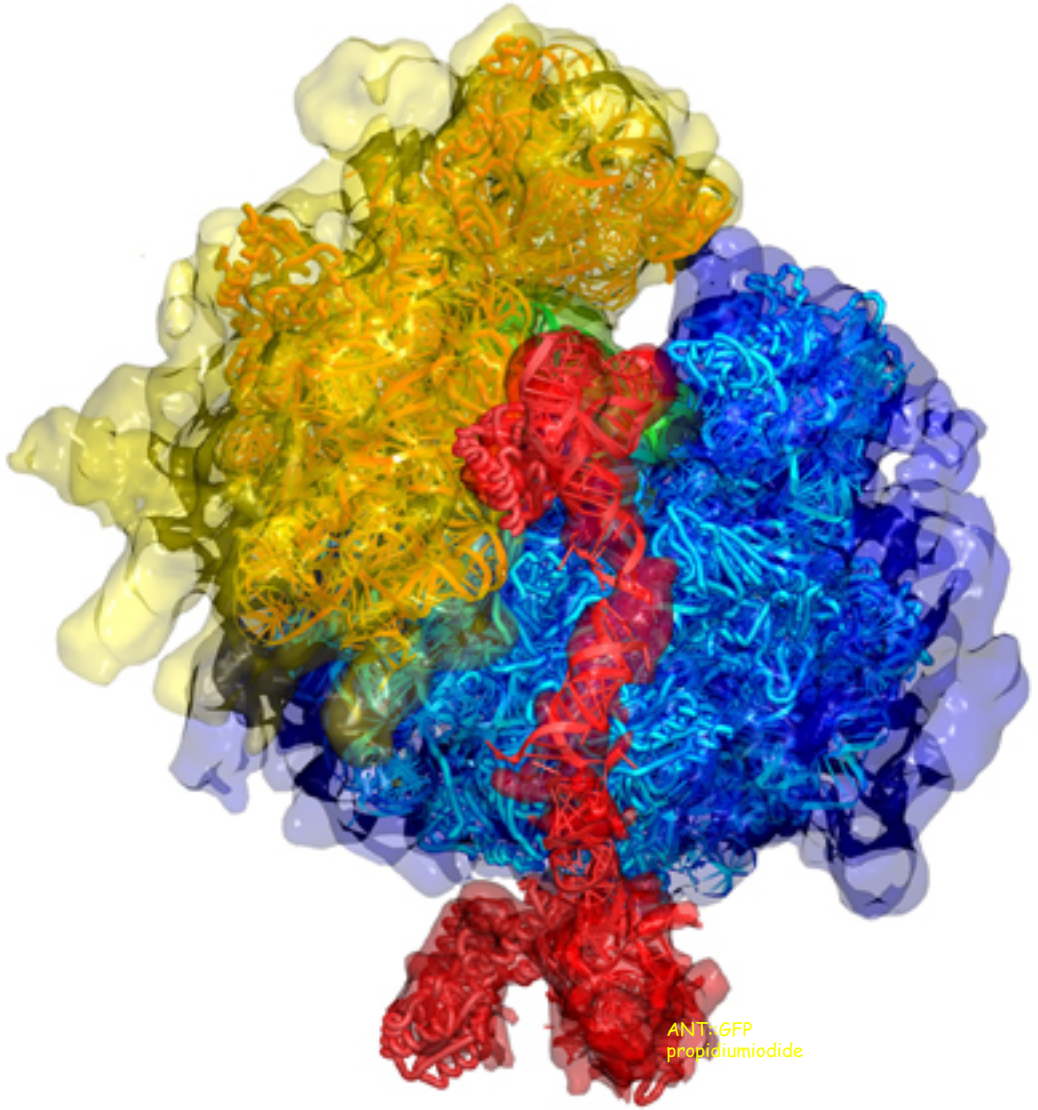
1990: les manipulations génétiques

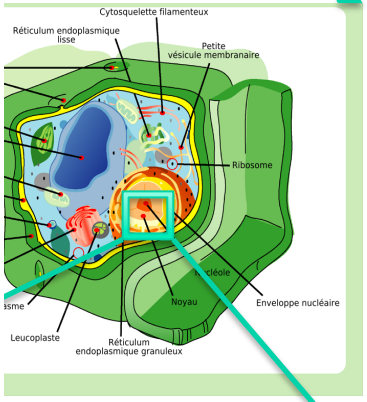


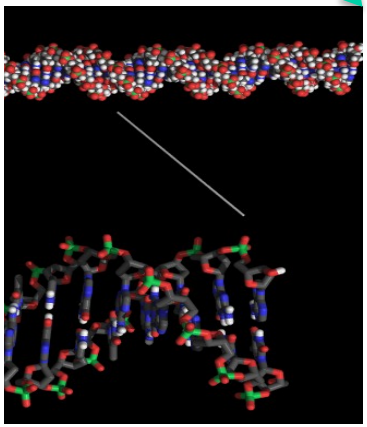







ANT:GFP
propidiumiodide

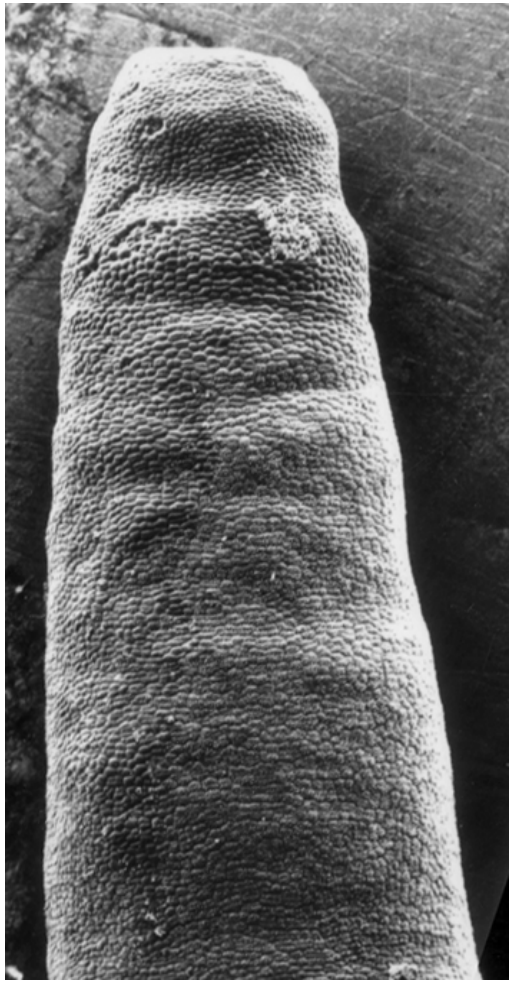

Cytosquelette filamenteux
Réticulum endoplasmique lisse
Petite vésicule membranaire
Ribosome
Noyau
Enveloppe nucléaire
Leucoplaste
Réticulum endoplasmique granuleux



Mutants

Plante
Arabidopsis

Mutant pin 1



pin 1

Mutants de la fleur

agamous (ag)

ap3 or pistillata (pi)

apetala1 (ap1)

apetala2 (ap2)

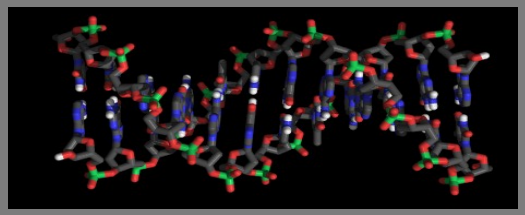
Exemples de mutants de la fleur

4 types d'organes, 3 genes (A, B, C) impliqués

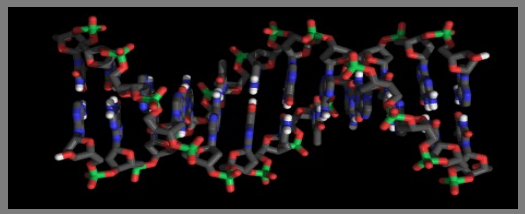
Que se passe t'il ?

Une énigme à résoudre …

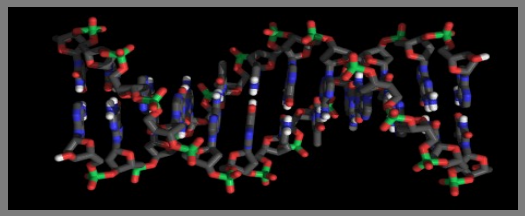
A



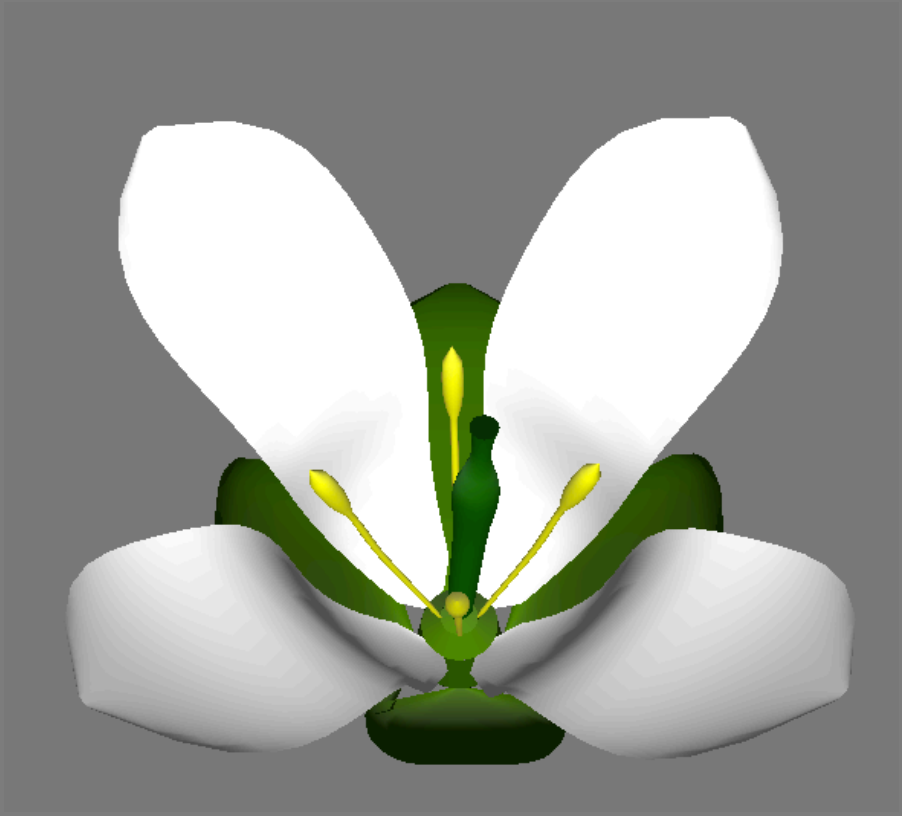
B



C

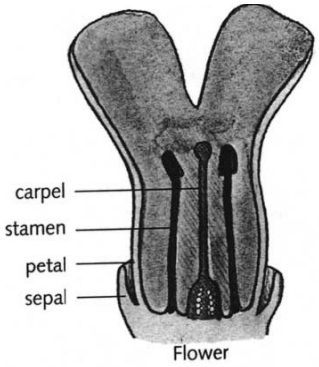


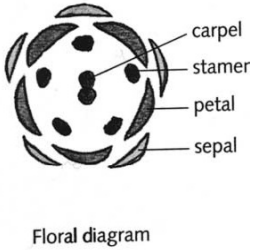
?

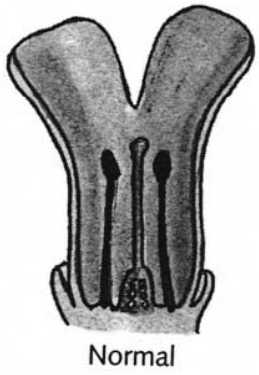


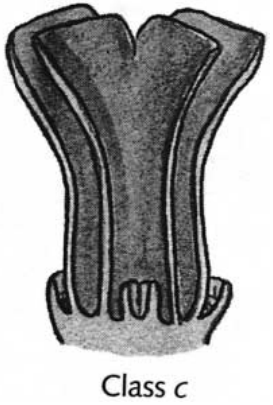
Le modèle ABC

(Coen, Meyerowitz, Nature, 1991)

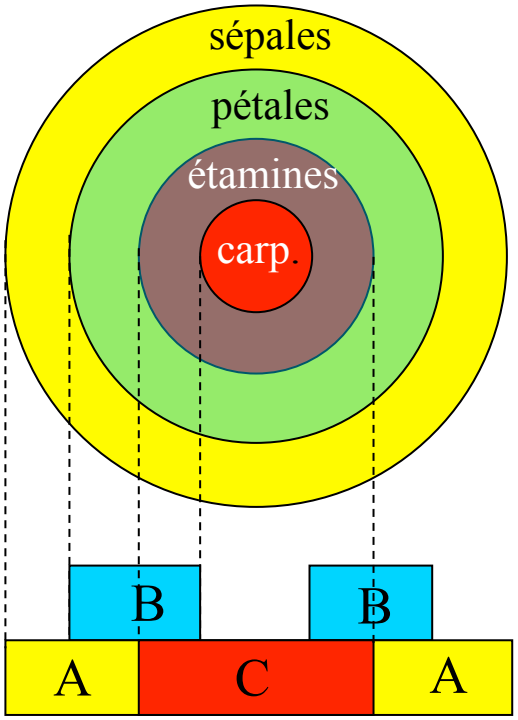


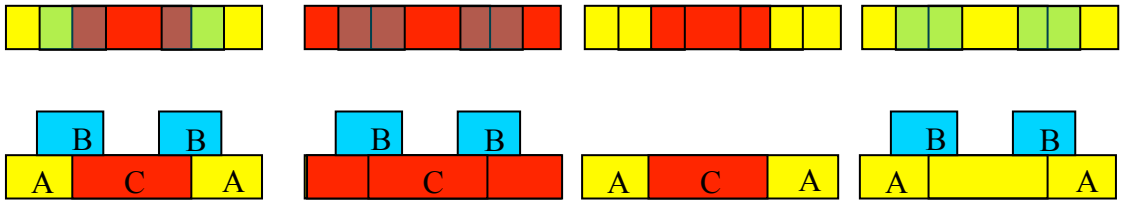


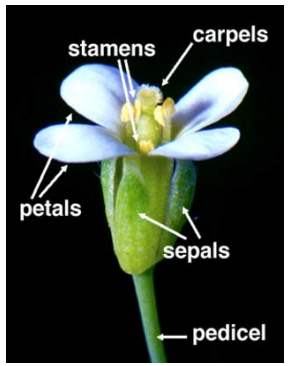


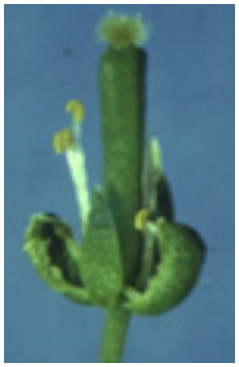


(Coen, 2000)





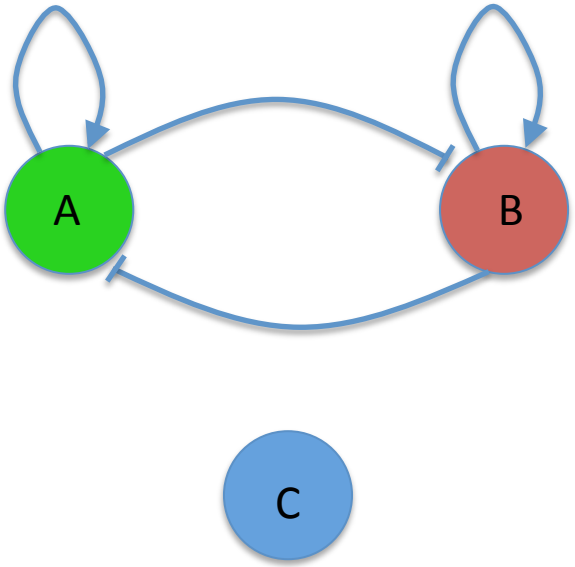




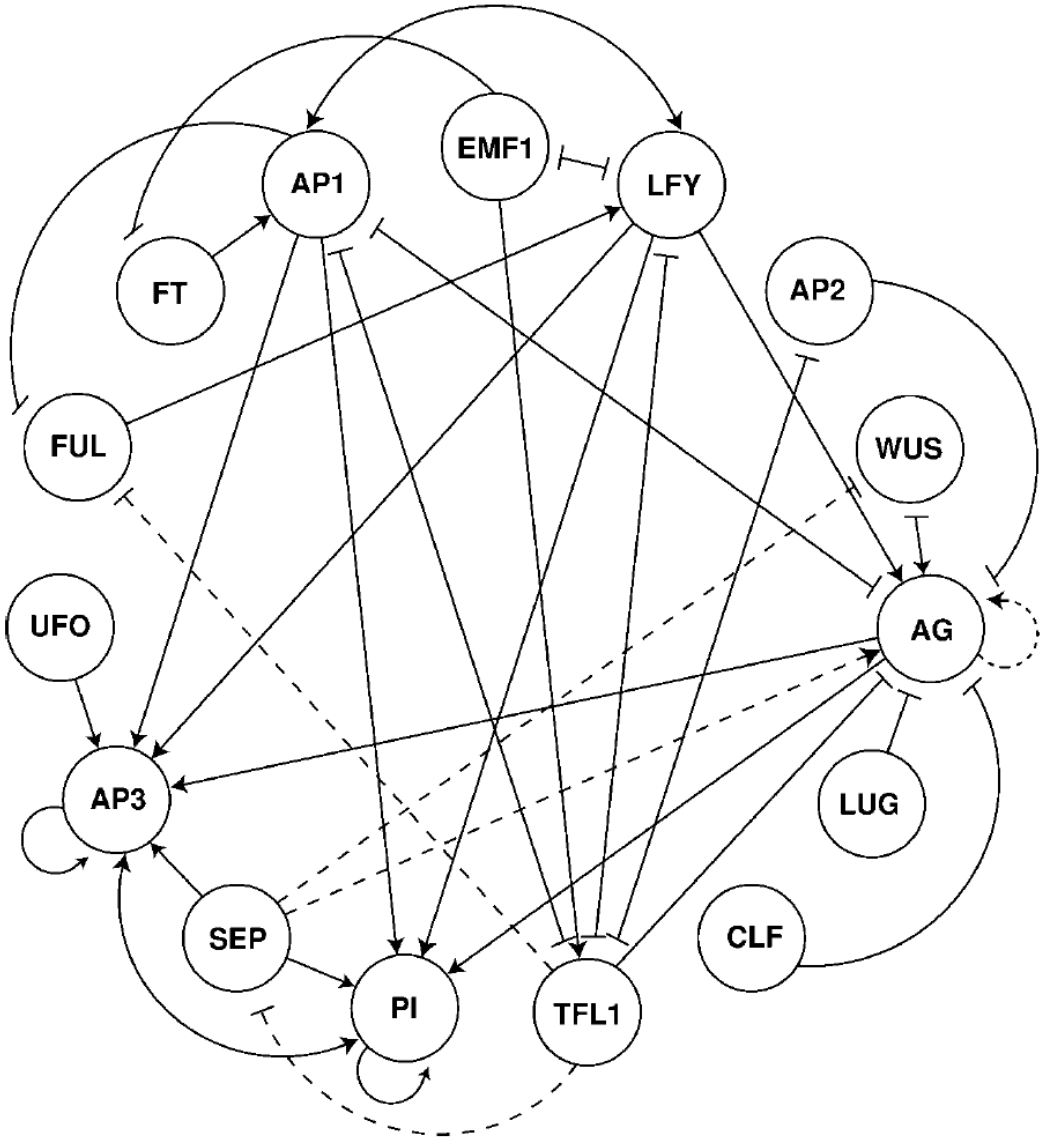
Type sauvage

(Photos: Meyerowitz et Yanofsky)

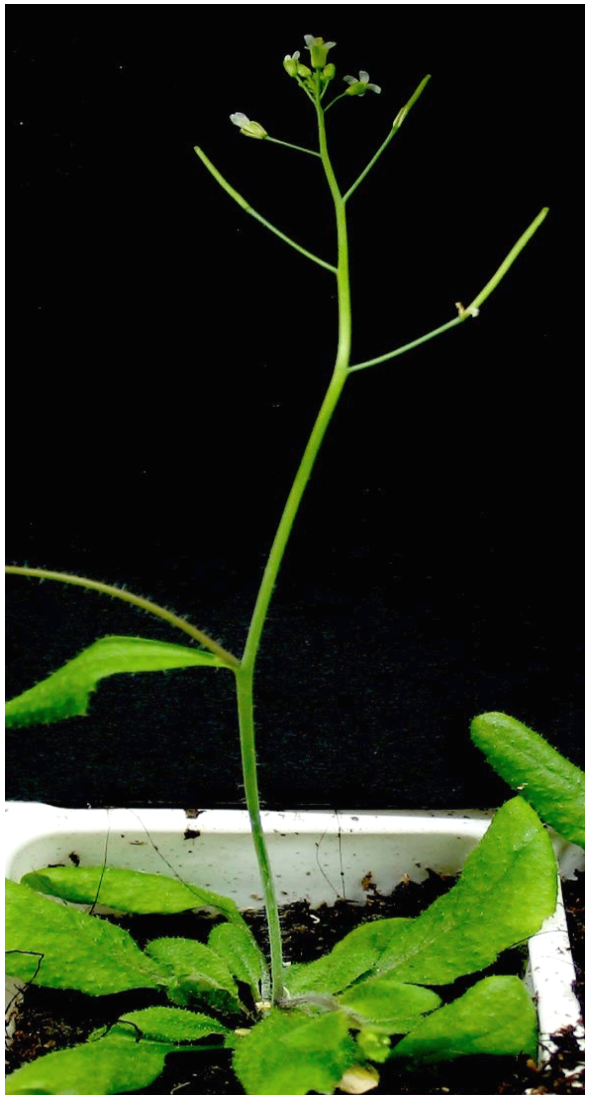
ABC: un système de Turing !



Depuis, ça se complique !



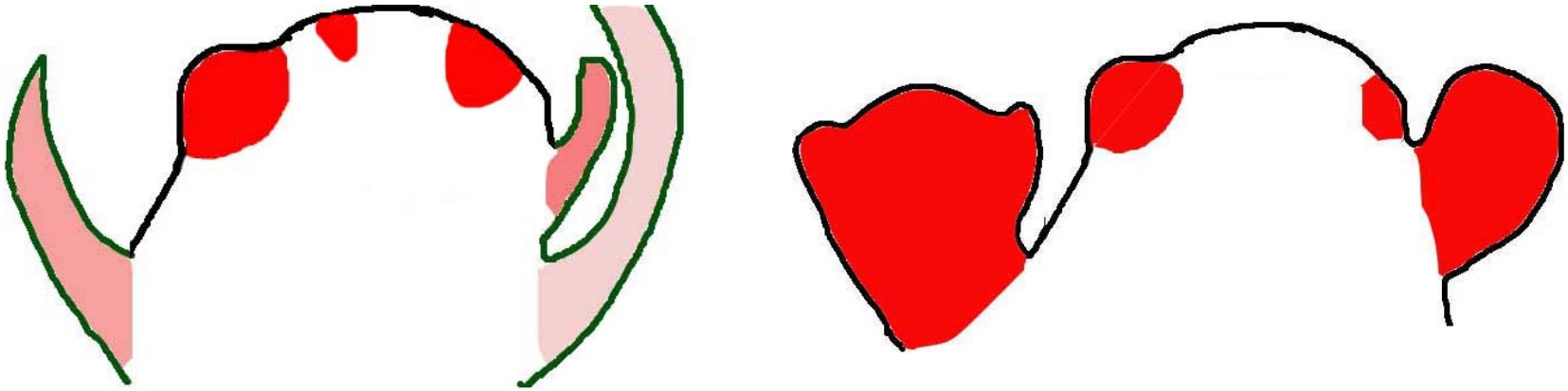
Exemple: rôle du gène *LEAFY*



sauvage

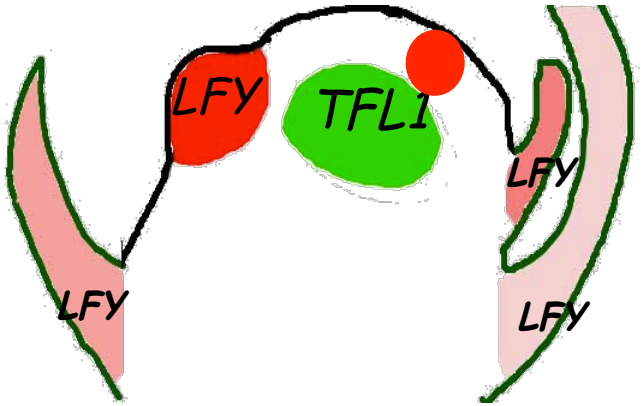
mutant *leafy*

LEAFY s'exprime dans les bourgeons floraux

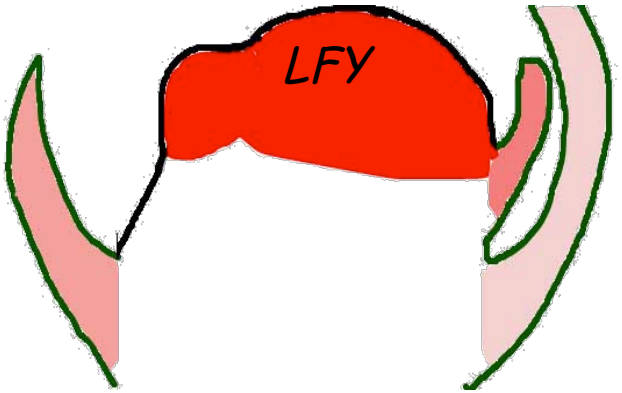


Role du gène TERMINAL FLOWER 1 (TFL1)

mutant *tfl1*



sauvage

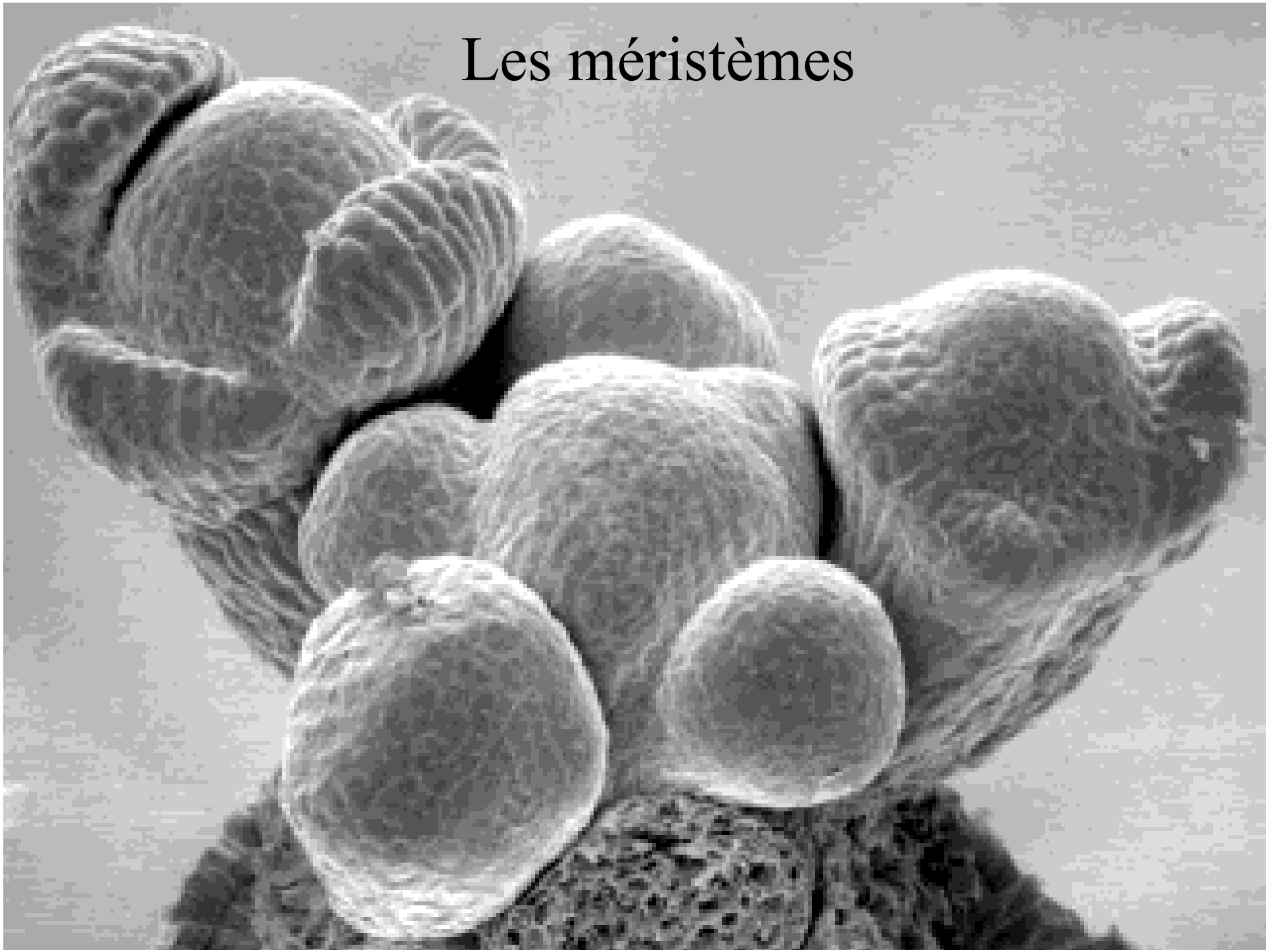


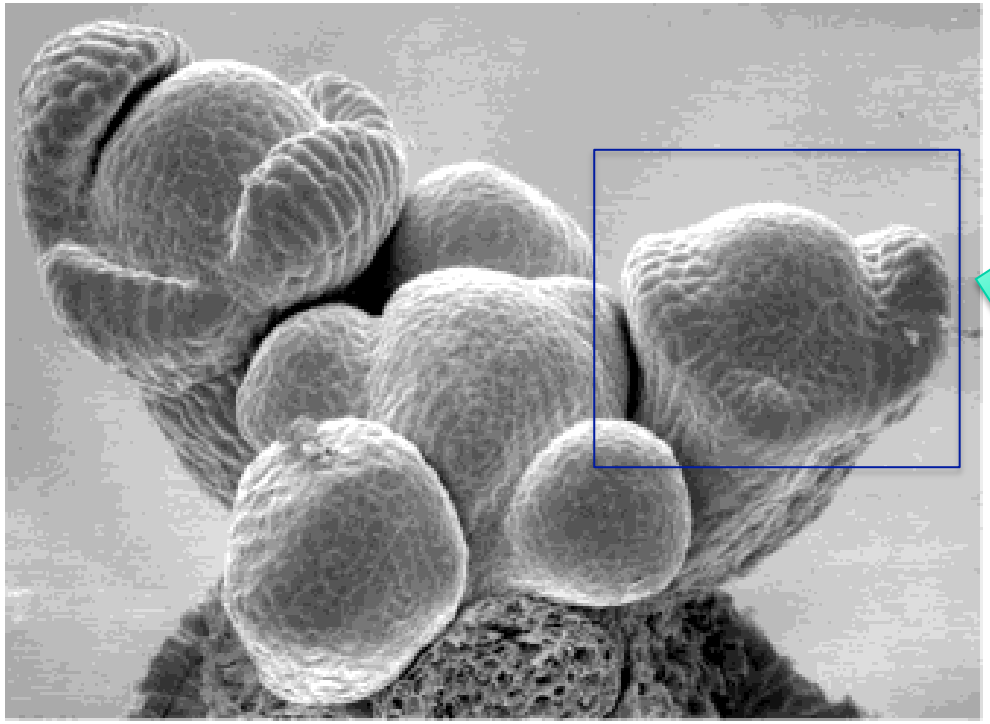
tfl1 mutant

TFL1 réprime LFY

Casser le code complet:
un travail d’équipe !

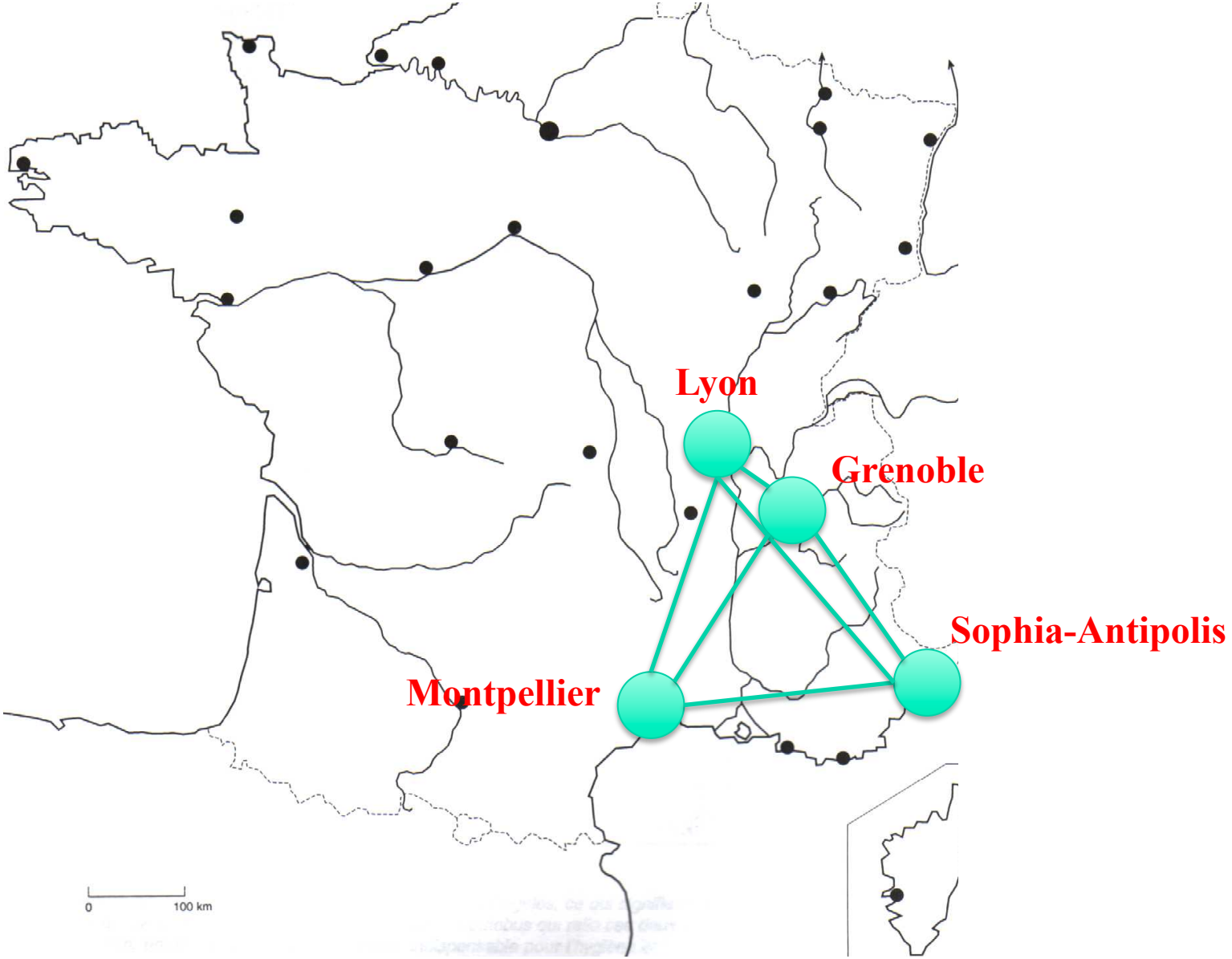
Les méristèmes



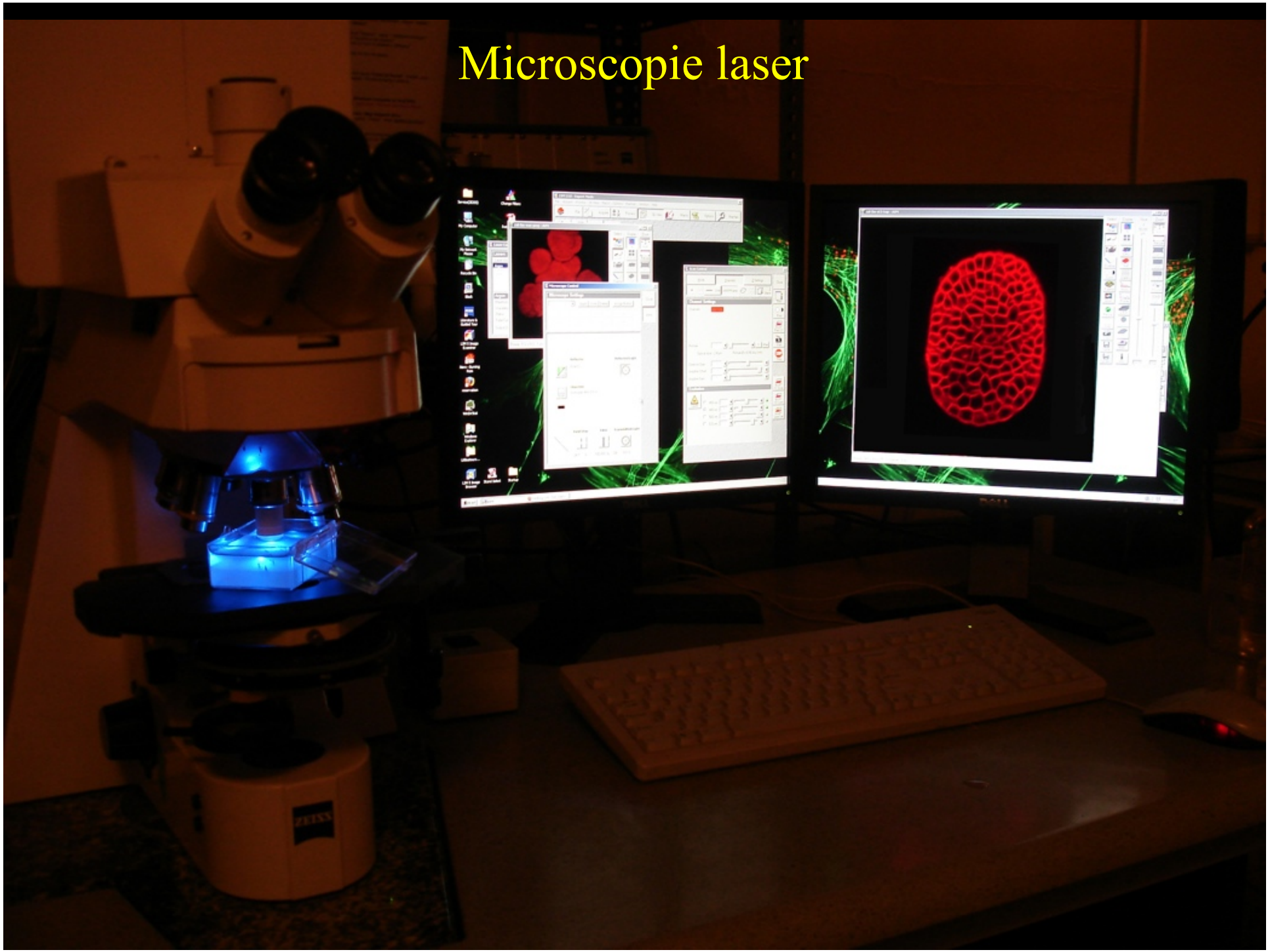


?

Un réseau d'équipes de recherche

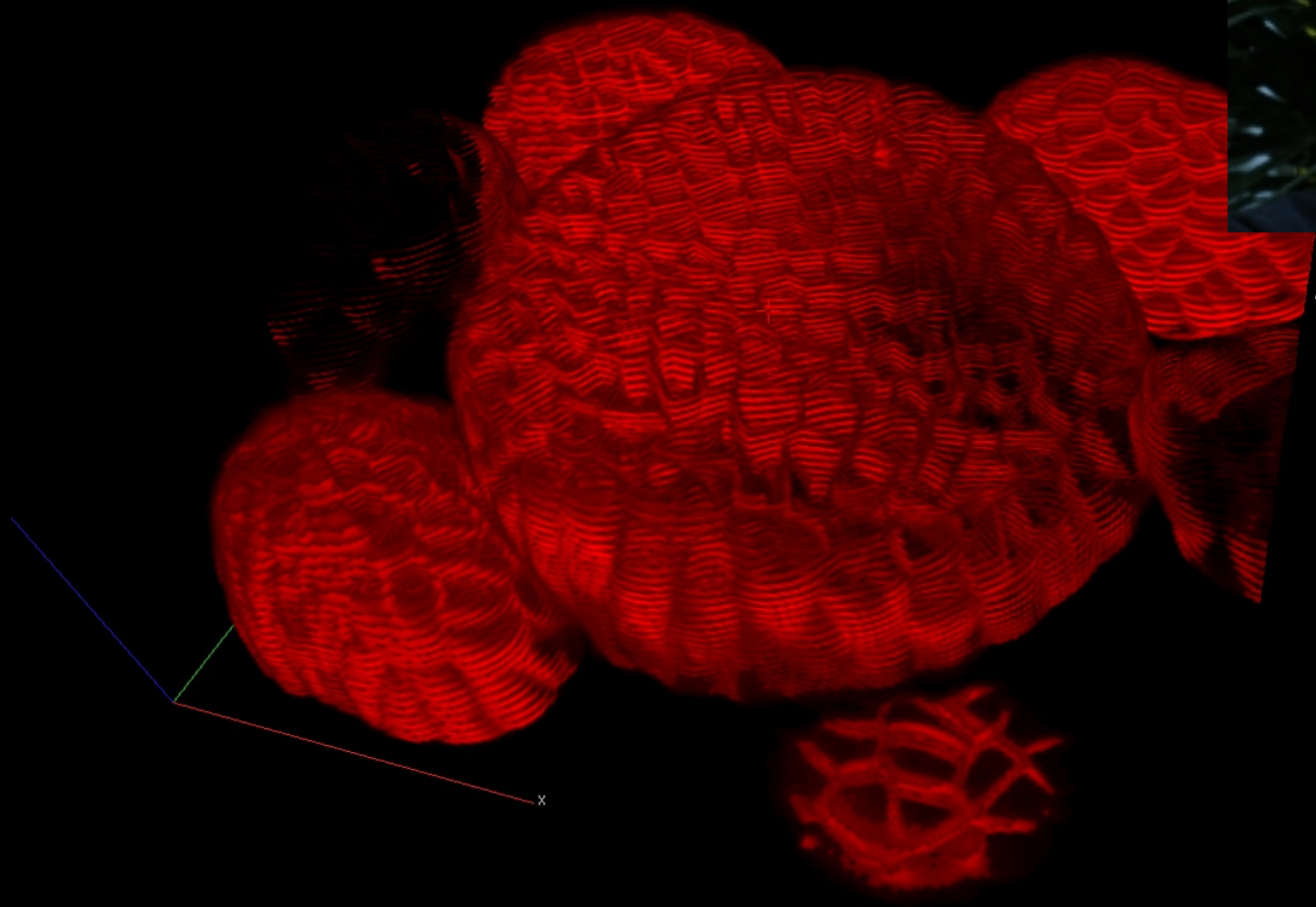


Microscopie laser

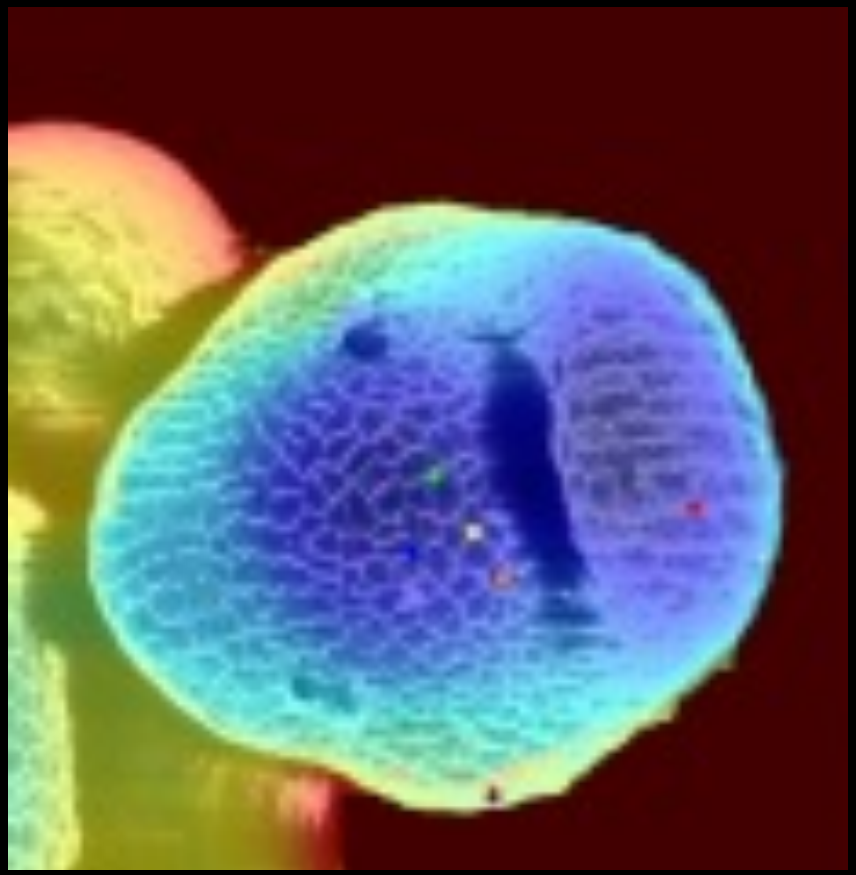


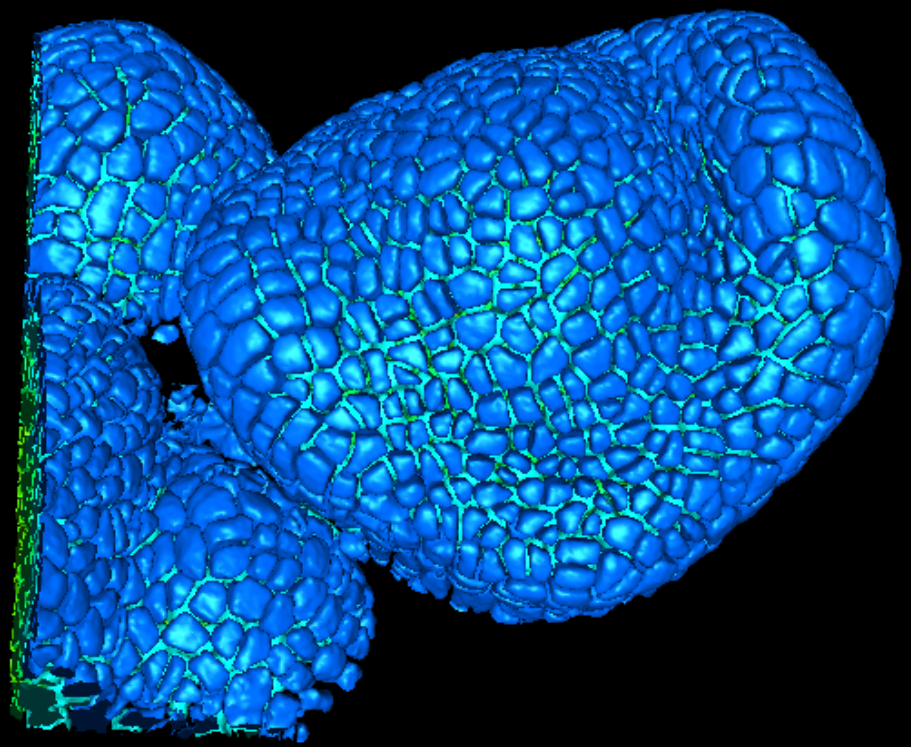
Images en volume

P. Das,, ENS-Lyon

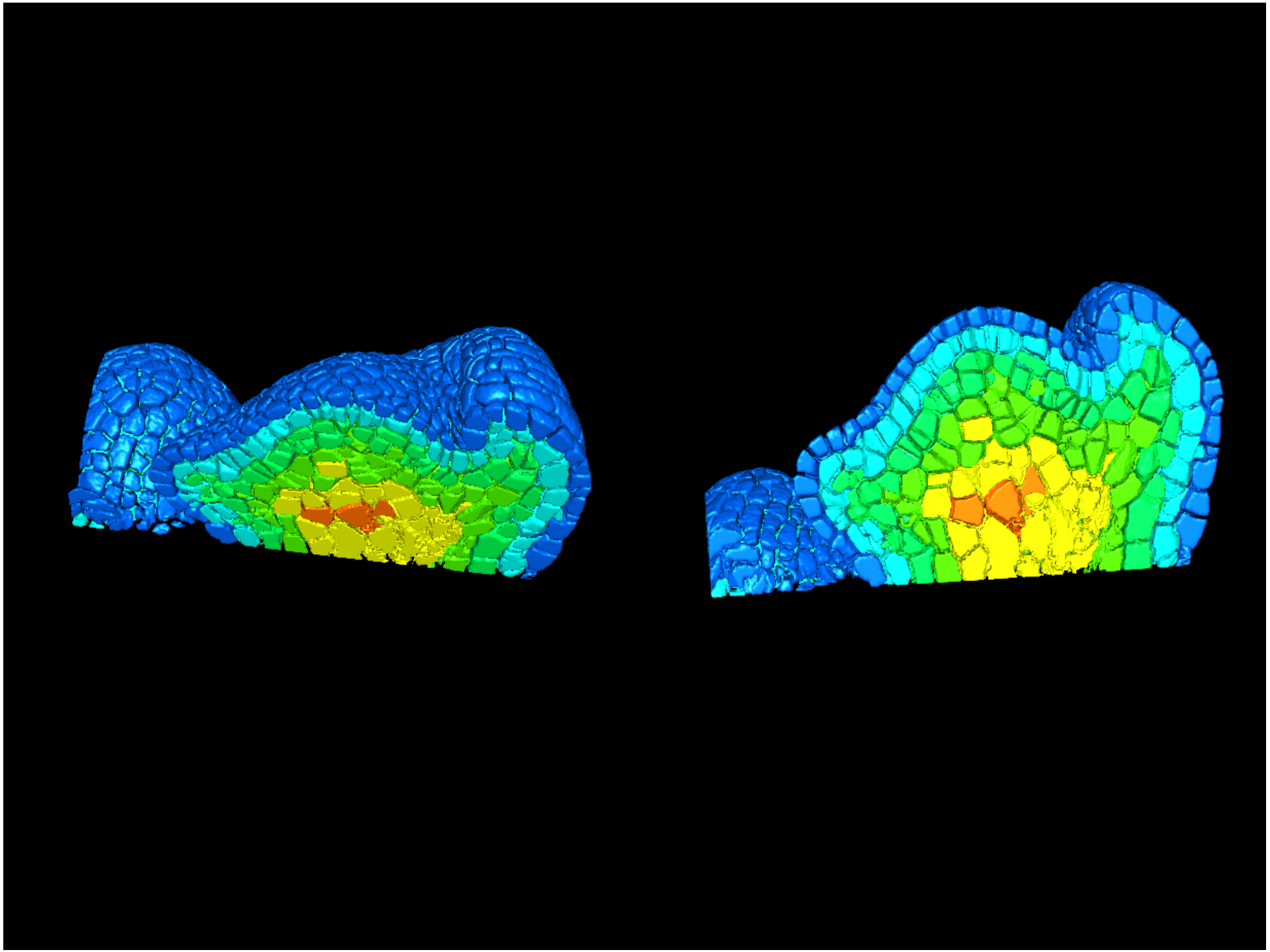


Reconstruction automatique en 3D

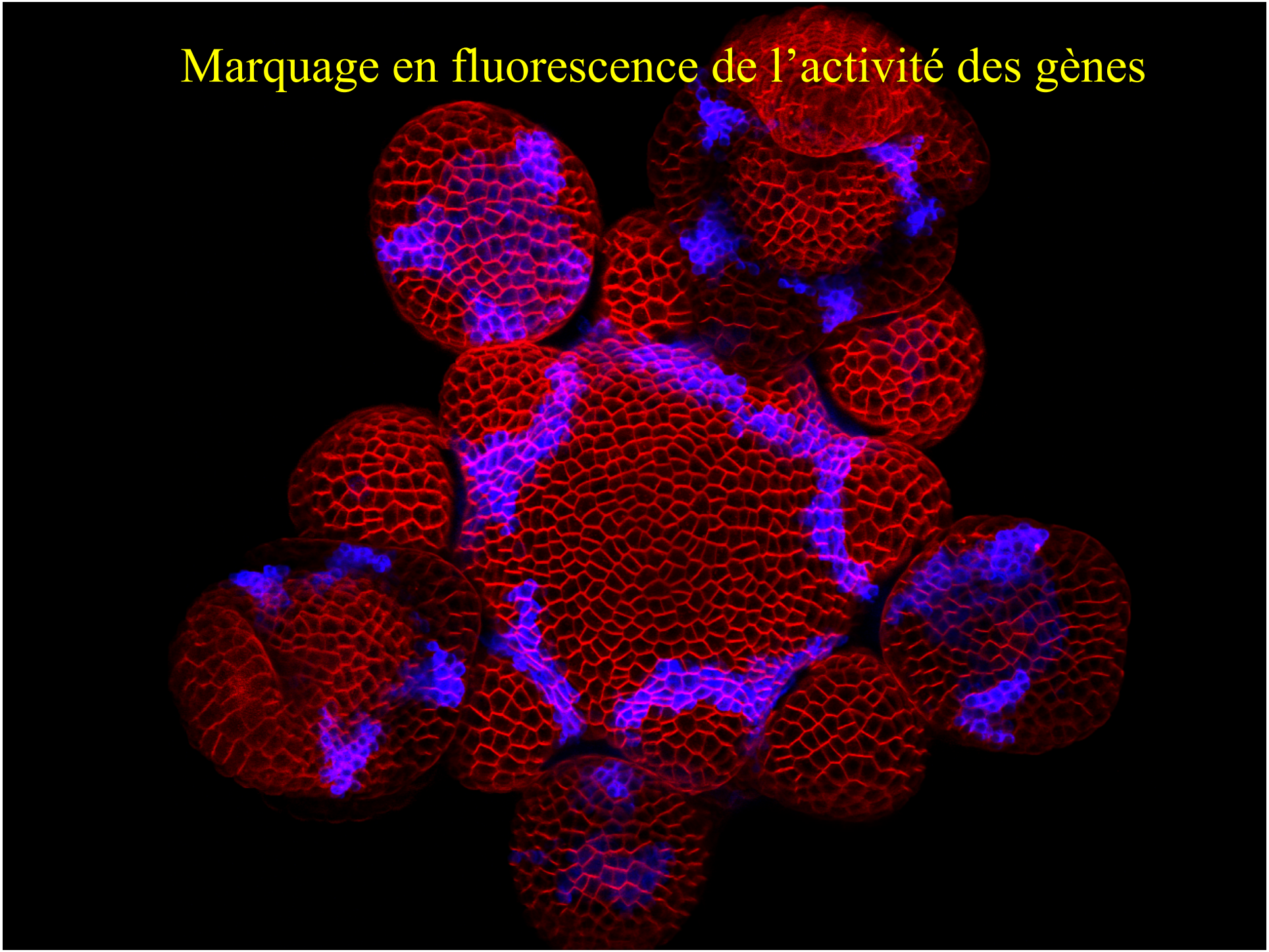




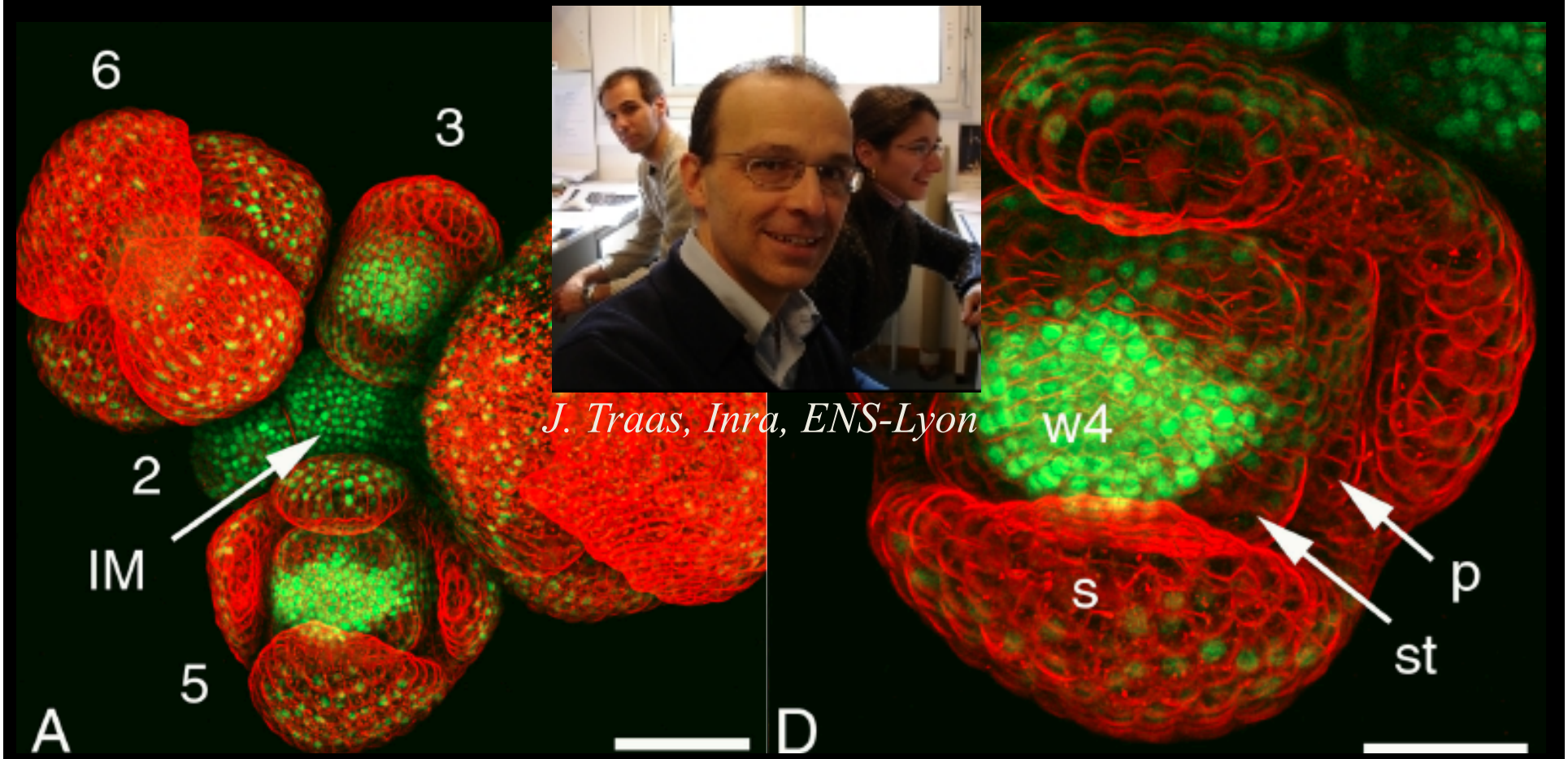
Collab. *EPI Asclepios (G. Malandain)*
Arabidopsis, ENS-Lyon (J. Traas, P. Das)



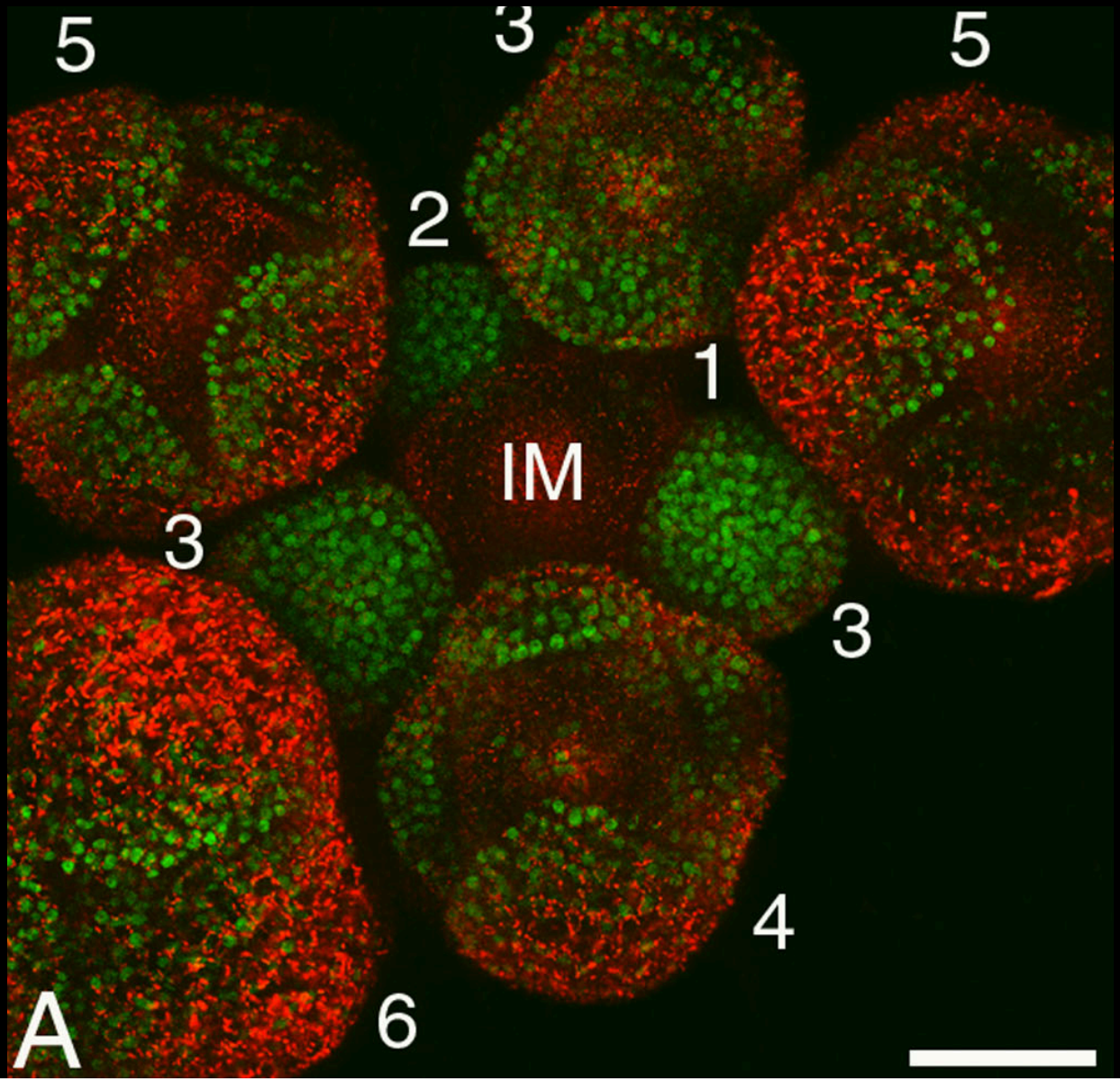
Marquage en fluorescence de l'activité des gènes

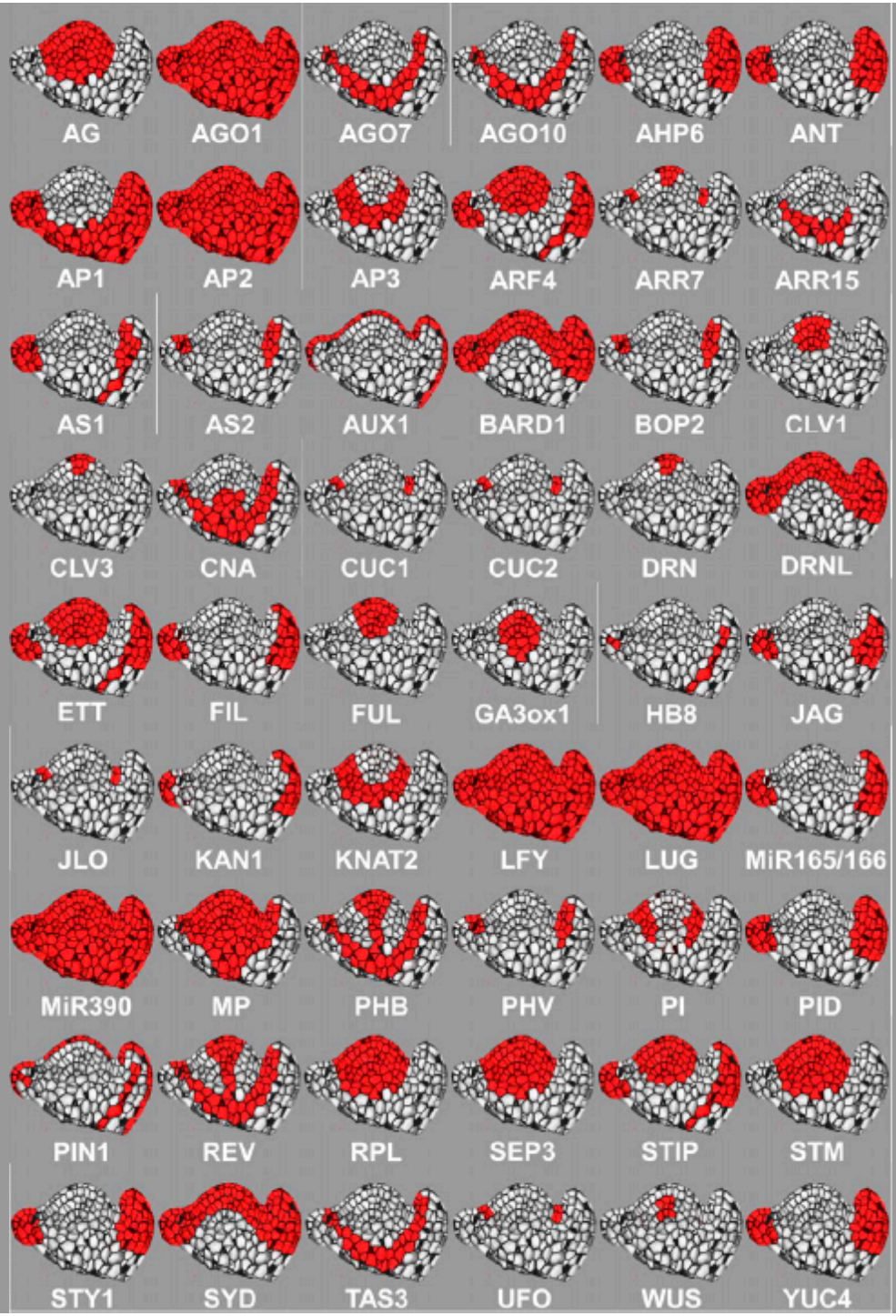


Observer l'activité des gènes A, B, C, ...



Exemple: localisation GFP du Gène A (AP1)

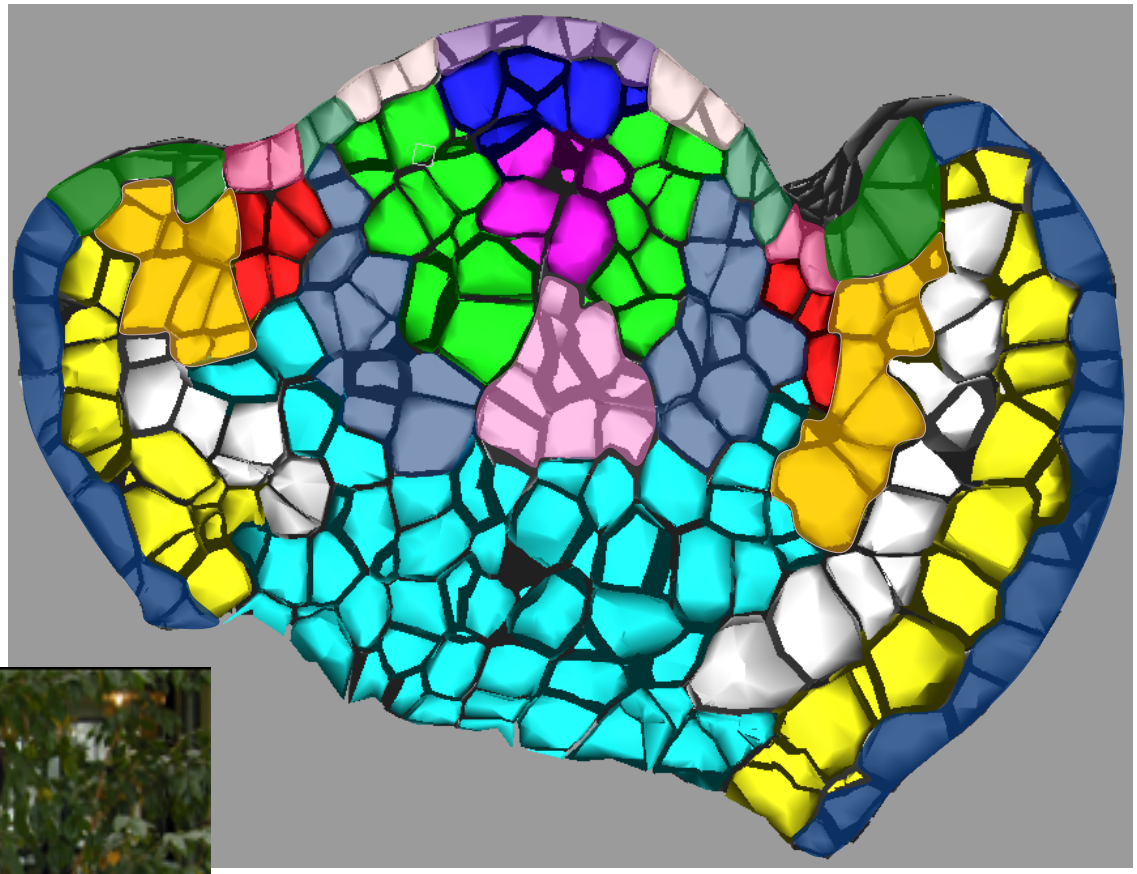




(La Rota et al.,
The Plant Cell, 2011)

36 Transcription factors in 16 domains

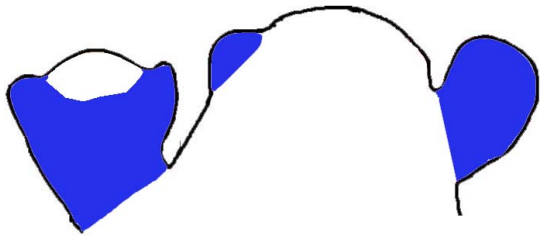
Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
AG	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1
AHP6	0	0	0	0	0	0	1	1	1	0	1	1	0	0	0	0
ANT	0	0	0	0	0	0	1	1	1	0	1	1	0	0	0	0
AP1	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0
AP2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
AP3	0	0	0	1	1	1	0	0	0	0	0	0	1	1	0	0
ARF4	1	1	1	1	1	0	0	1	1	0	1	0	0	1	1	1
AS1	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0
AS2	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0
AtHB8	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
AtML1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
BOP2	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0
CNA	0	0	0	0	1	0	1	0	0	1	0	1	0	0	0	0
CUC1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0
CUC2	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0
DRN	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
DRNL	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1
ETT	1	1	1	1	1	0	0	1	1	0	1	0	0	1	1	1
FIL	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0
FUL	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1
JAG	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
JLO	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0
KAN1	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0
KNAT2	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0
LFY	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
MP	1	1	1	1	1	1	1	0	0	1	0	1	1	1	1	1
PHB	1	1	1	0	1	0	1	0	0	1	0	1	0	0	1	1
PHV	0	0	0	0												
PI	0	0	0	1												
REV	1	1	1	0												
RPL	1	1	1	1												
SEP3	1	1	1	1												
STM	1	1	1	1												
STY1	0	0	0	0												
WUS	1	0	0	0												



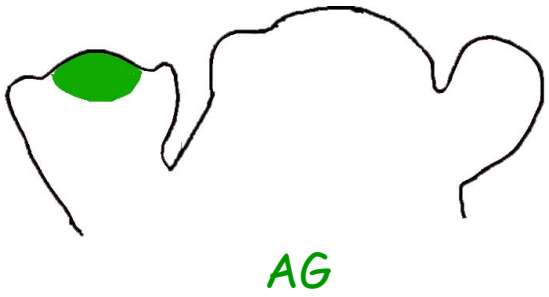
Françoise Monéger, ENS-Lyon

Triple mutant et expression des gènes ABC

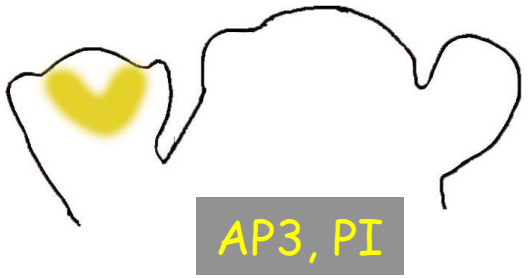
Expression de A

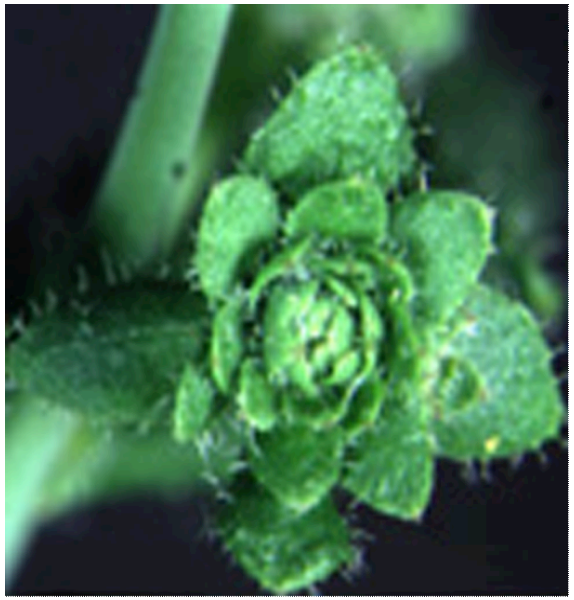


Expression de C



Expression de B

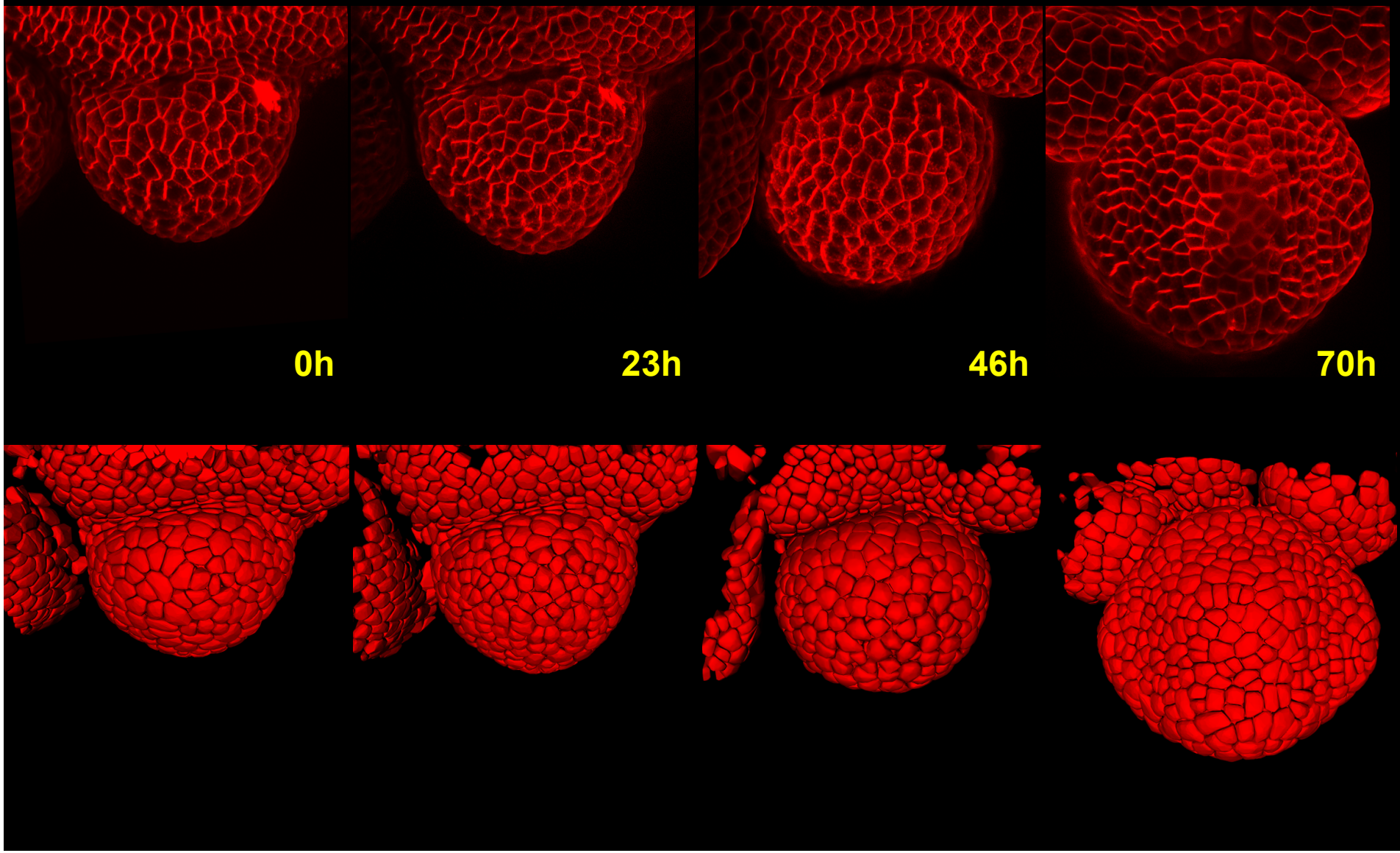




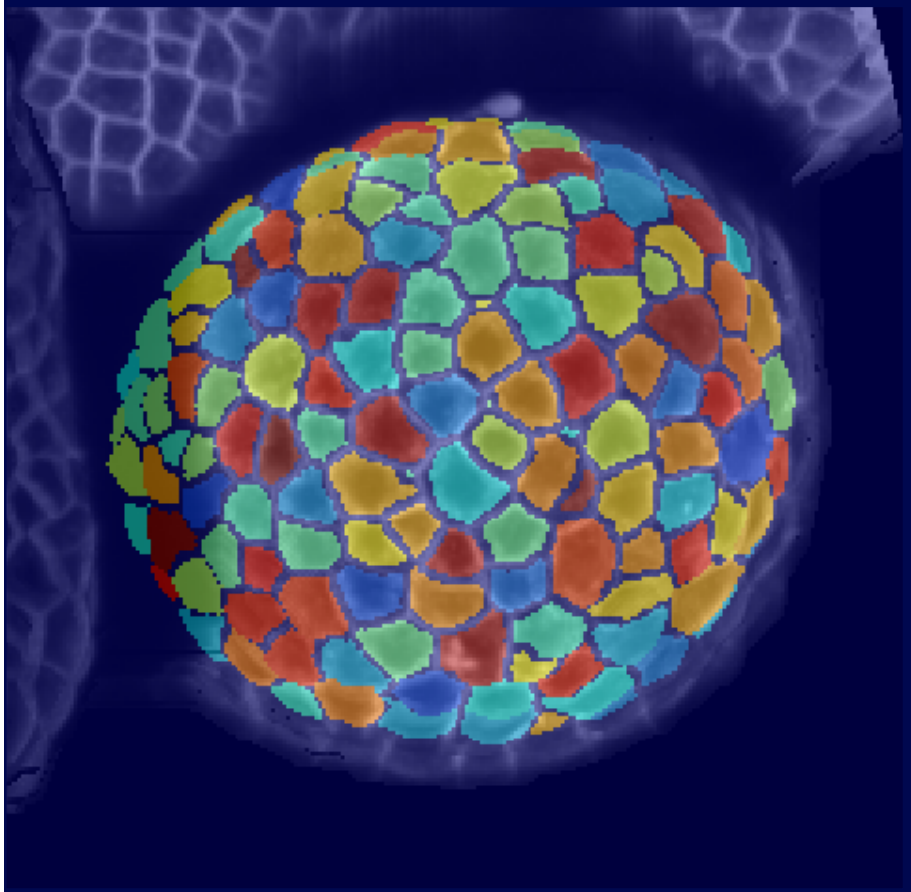
La prévision de Goethe dans « Die Versuchung der Metamorphose zu erklären (1790) » :

Les organes floraux sont des feuilles modifiées

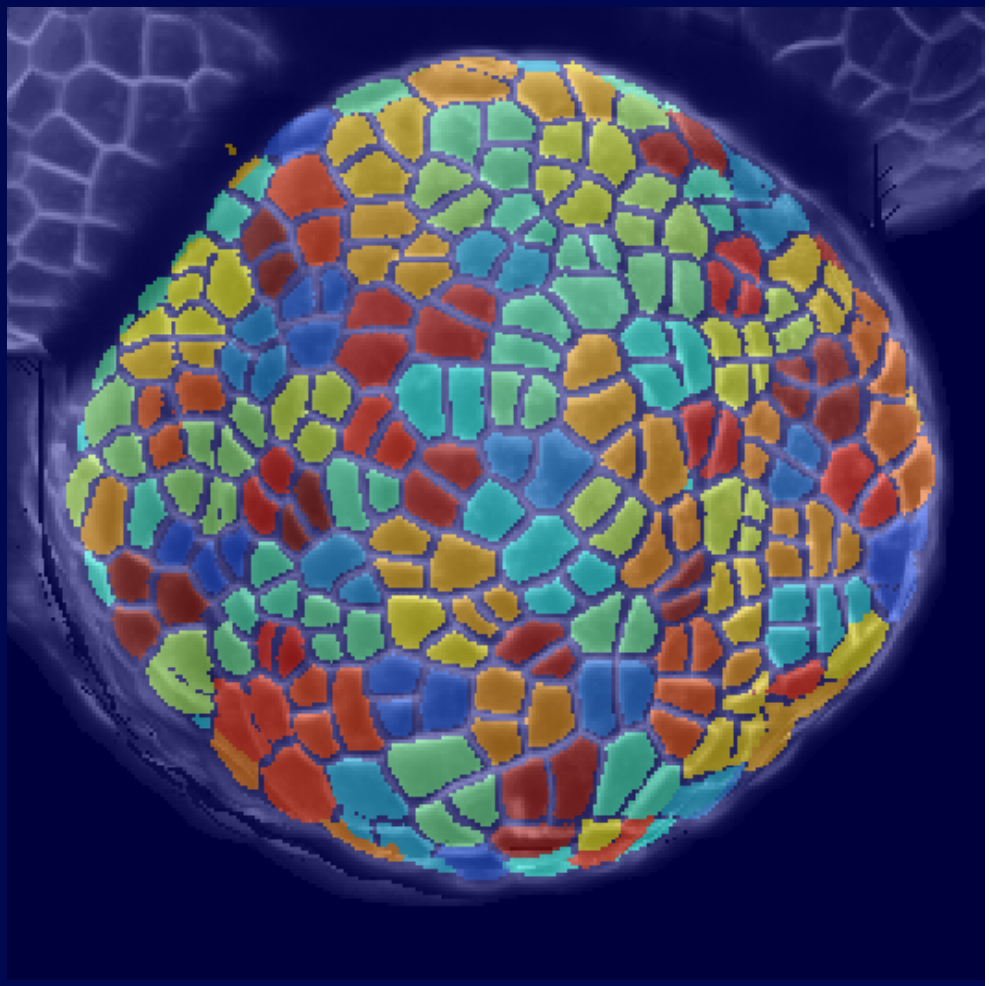
Suivi temporel



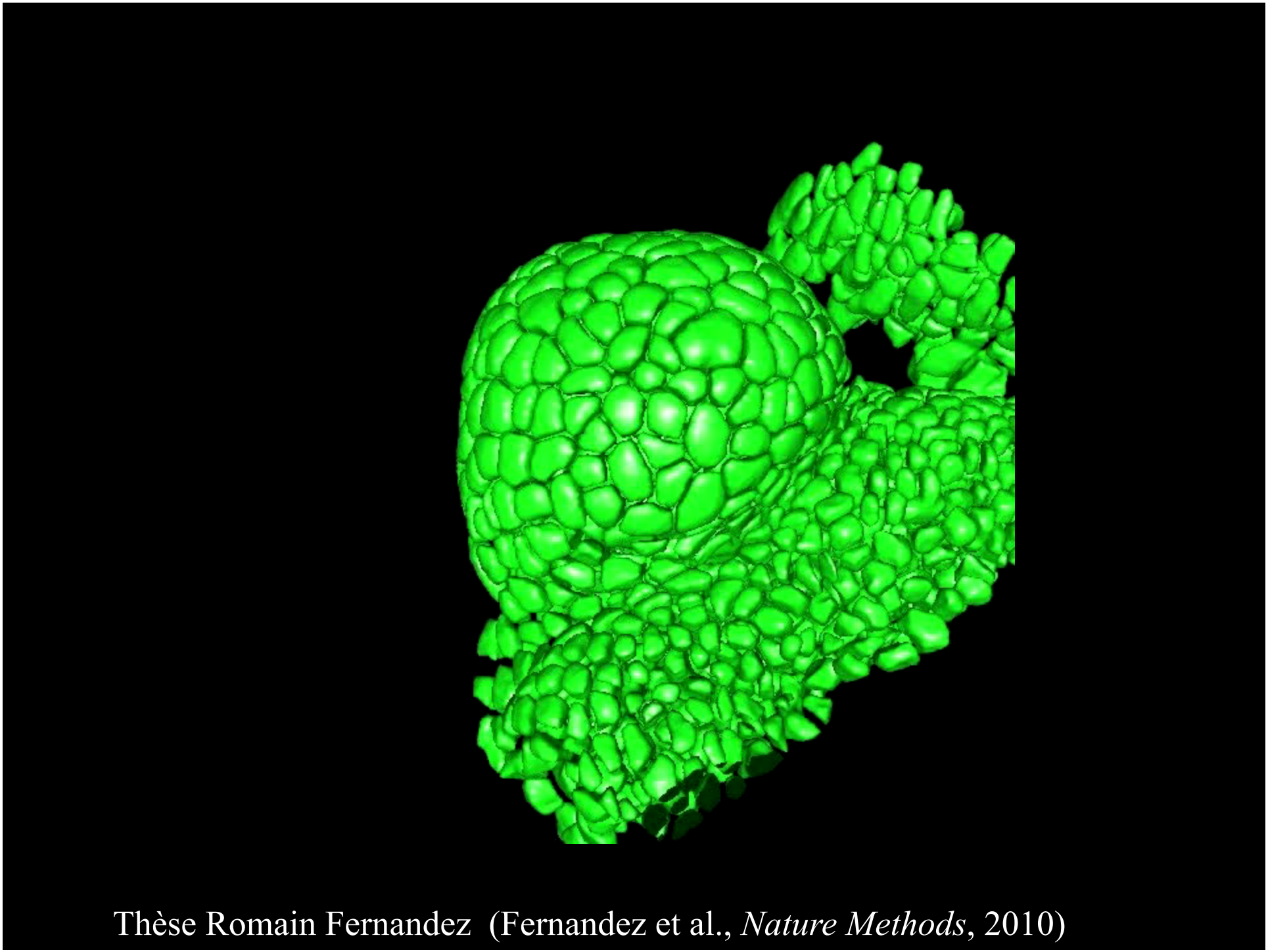
Suivi des lignées cellulaires



T0

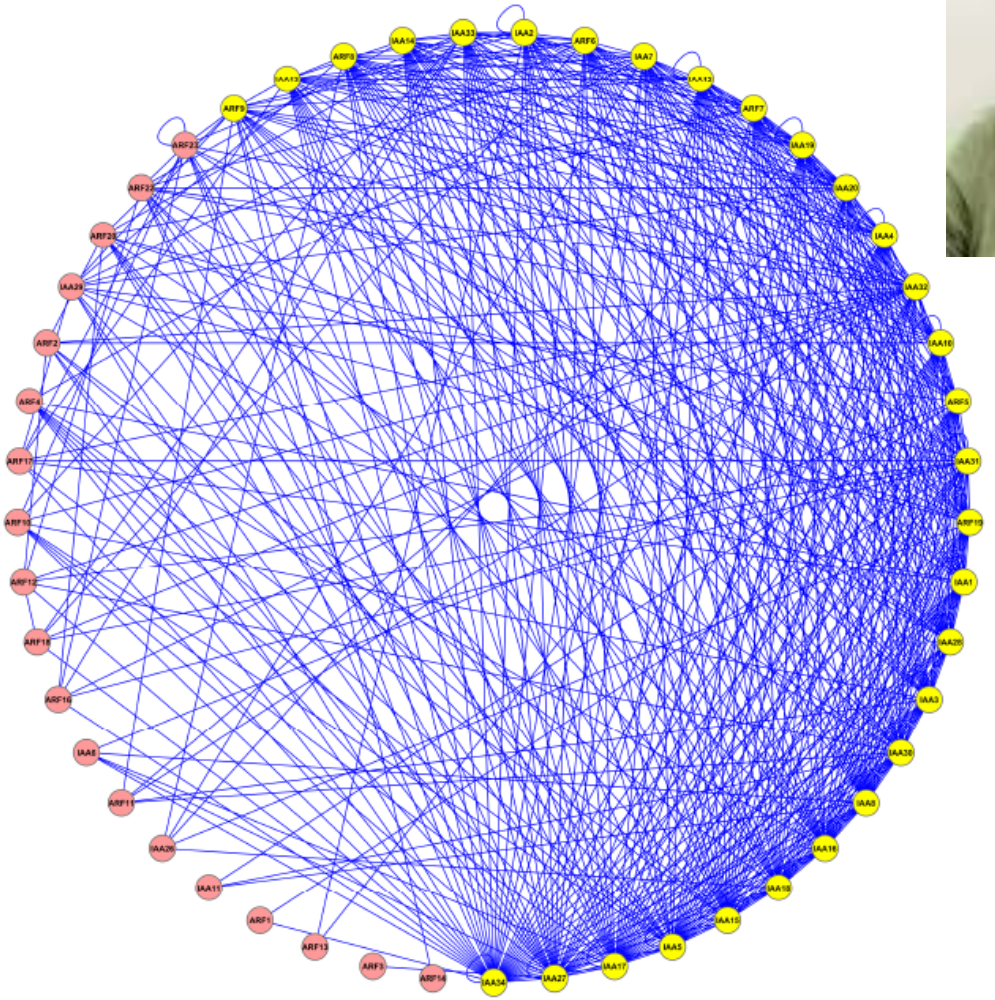


T0+24h



Thèse Romain Fernandez (Fernandez et al., *Nature Methods*, 2010)

Le dialogue entre gènes peut parfois devenir très complexe



Teva Vernoux

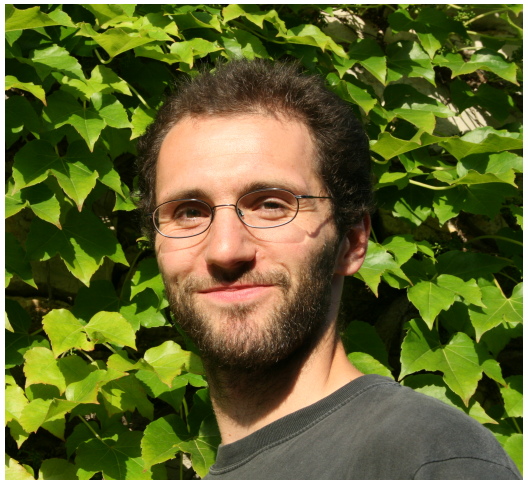
Ecriture mathématique du dialogue entre les gènes

$$
\begin{aligned}
\frac{da_1}{dt} &= \pi_1 r + 2k'_{11}d_{11} - 2k_{11}a_1^2 + k'_{12}d_{12} - k_{12}a_1a_2 - \delta_1(x \\
\frac{da_2}{dt} &= \pi_2 + 2k'_{22}d_{22} - 2k_2a_2^2 + k'_{12}d_{12} - k_{12}a_1a_2 - \delta_2a_2 \\
\frac{d(d_{11})}{dt} &= k_{11}a_1^2 - (k'_{11} + \delta_{11})d_{11} \\
\frac{d(d_{12})}{dt} &= k_{12}a_1a_2 + \beta'_{12}g_{12} - \beta_{12}gd_{12} - (k'_{12} + \delta_{12})d_{12} \\
\frac{d(d_{22})}{dt} &= k_{22}a_2^2 + \beta'_{22}g_{22} - \beta_{22}gd_{22} - (k'_{22} + \delta_{22})d_{22} \\
\frac{dr}{dt} &= h(g_{22}) - \delta_r r \\
\frac{dg_{22}}{dt} &= \beta_{22}gd_{22} - \beta'_{22}g_{22} \\
\frac{dg_{12}}{dt} &= \beta_{12}gd_{12} - \beta'_{12}g_{12} \\
g &= 1 - g_{12} - g_{22}
\end{aligned}
$$

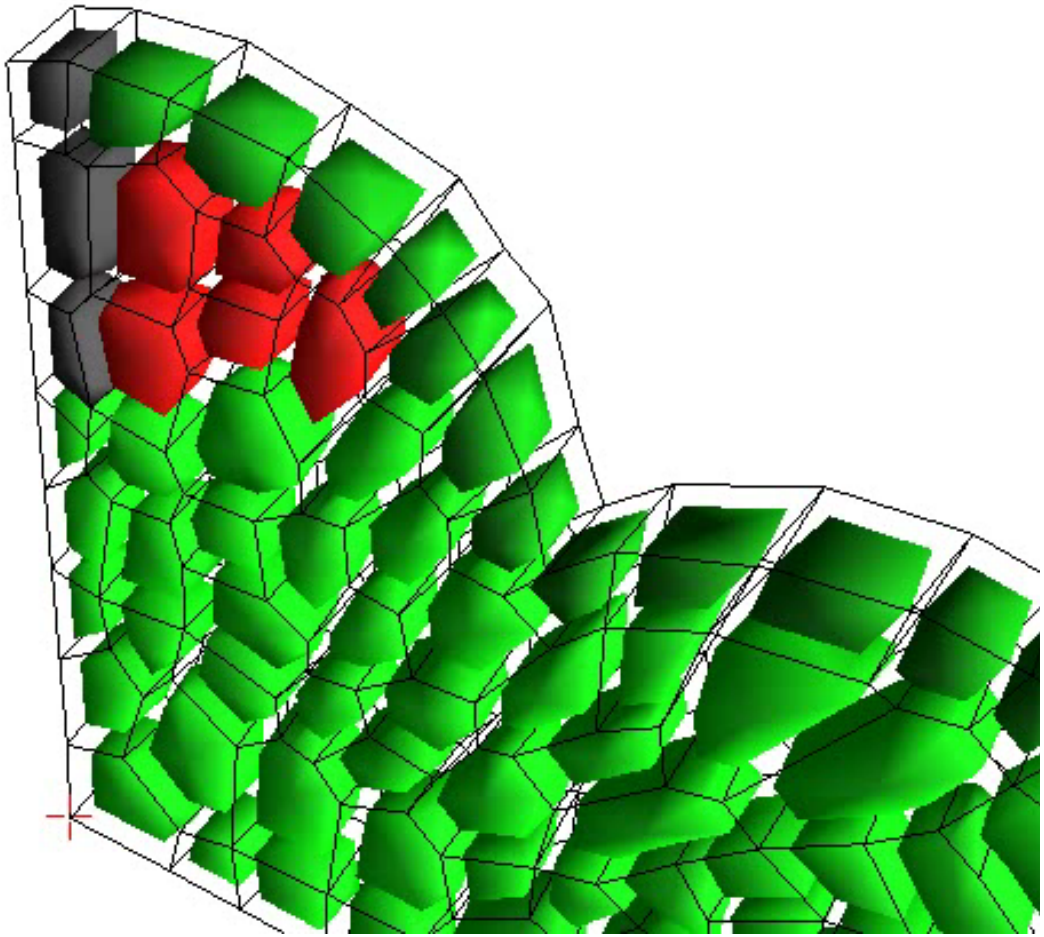
Etienne Farcot, Inria

Anna-Maria Kiss, Inra

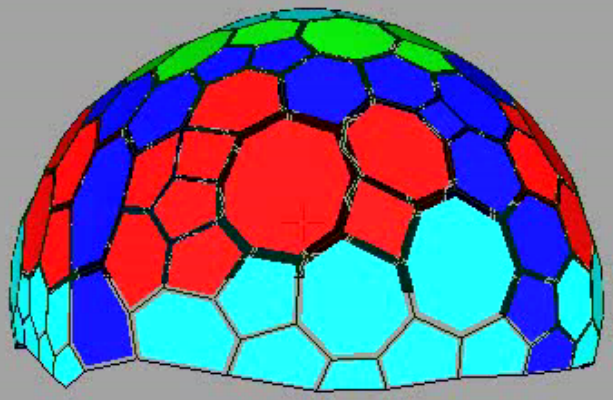
Simulation mécanique des interactions entre cellules

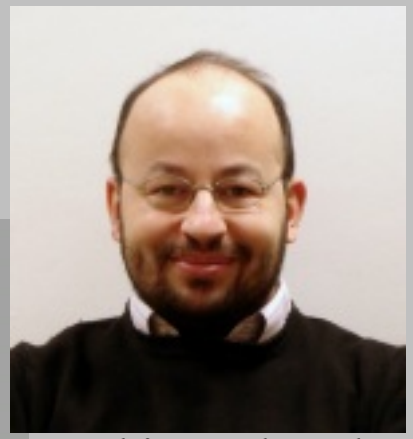


Jérome Chopard, Post-doc Inria



Simulation du développement d'une jeune fleur





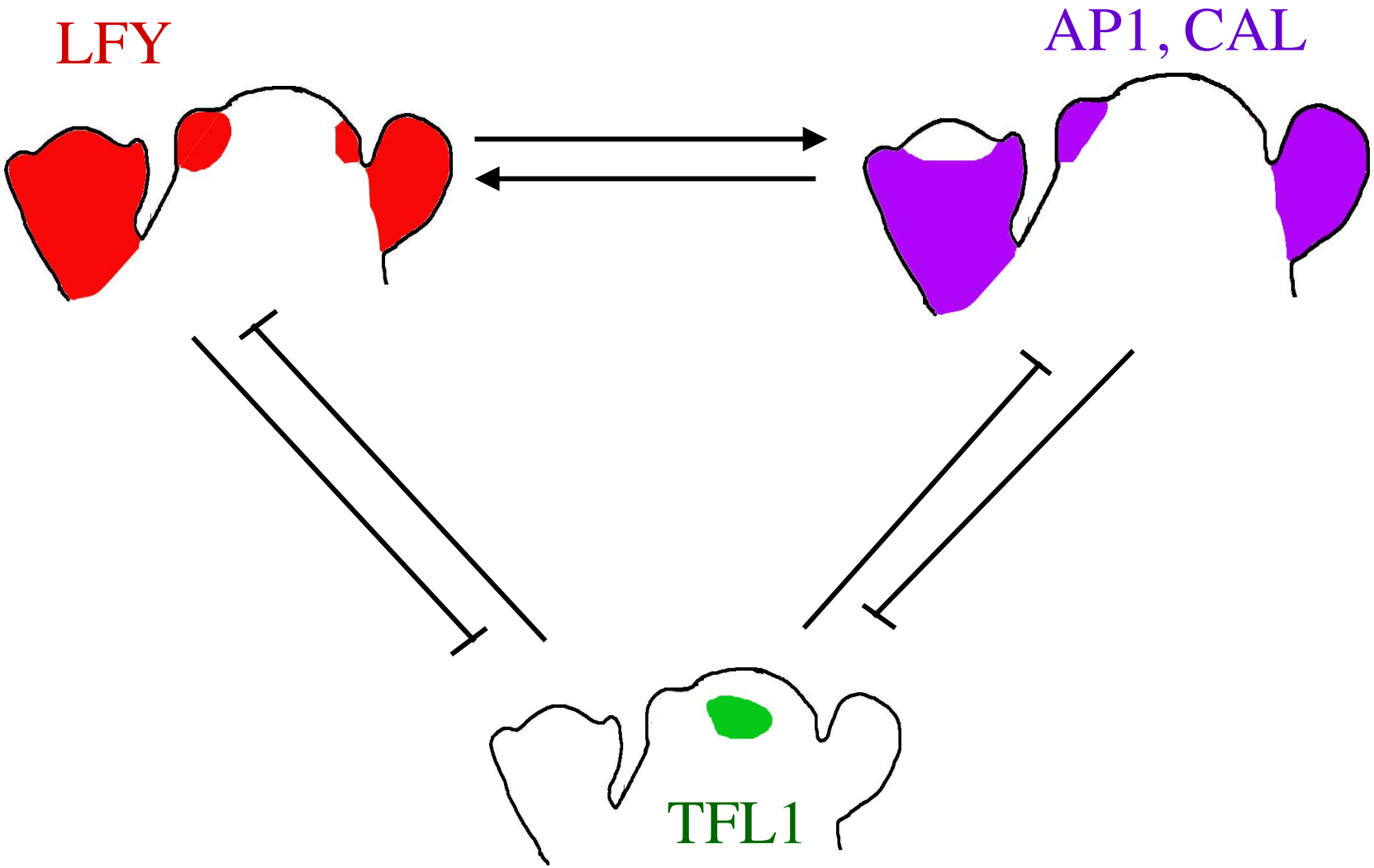
Arezki Boudaoud,
ENS-Lyon

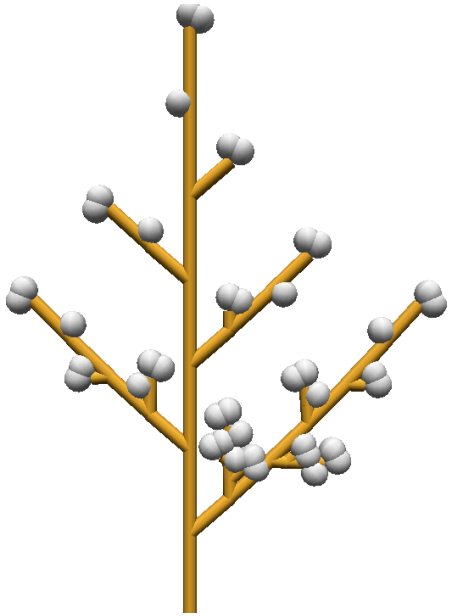
Frédéric Boudon,
Cirad

Modèles à des échelles plus intégrées

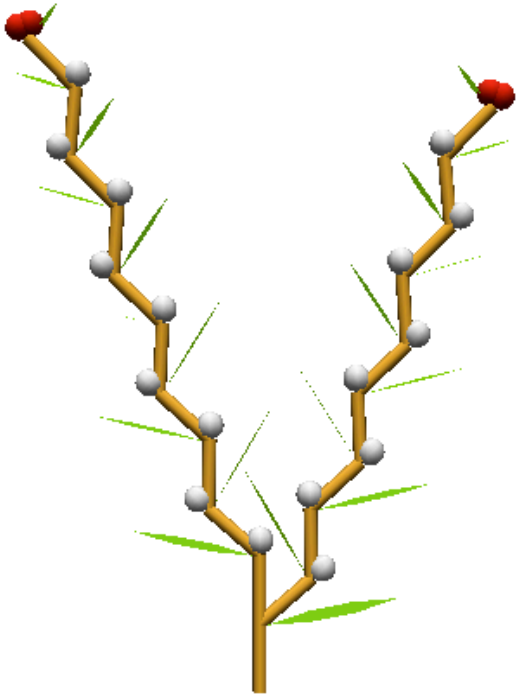
François Parcy, Cnrs

Le réseau de régulation des gènes d'identité méristématique

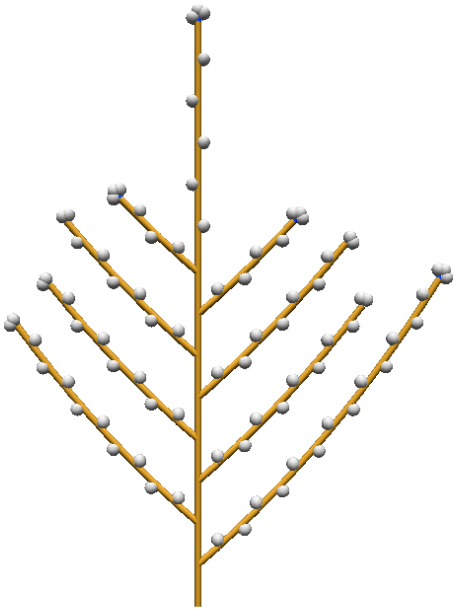




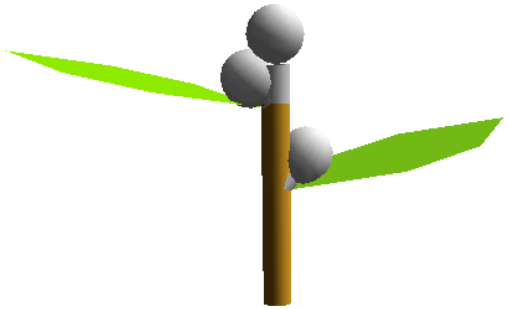
Panicle



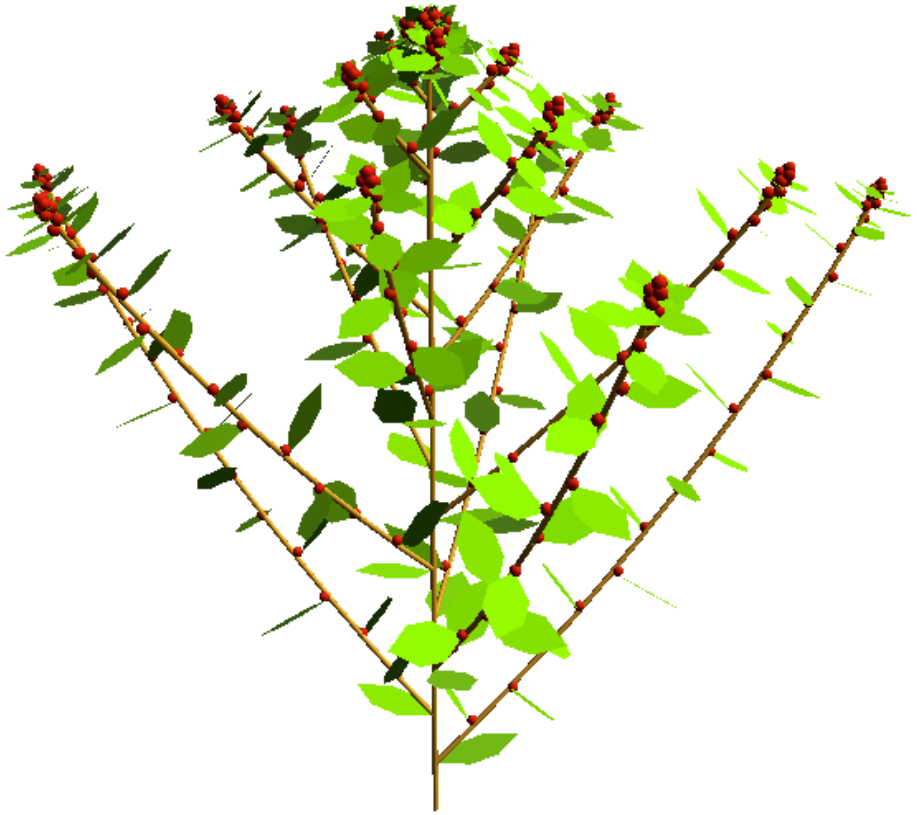
Cyme



Maize tassel

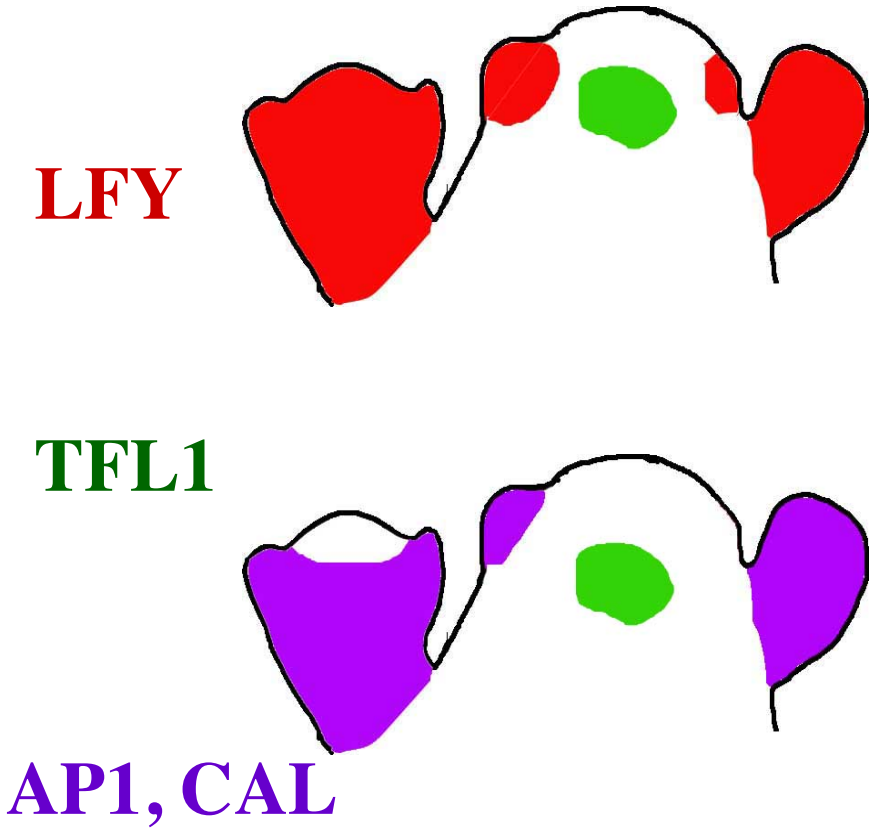


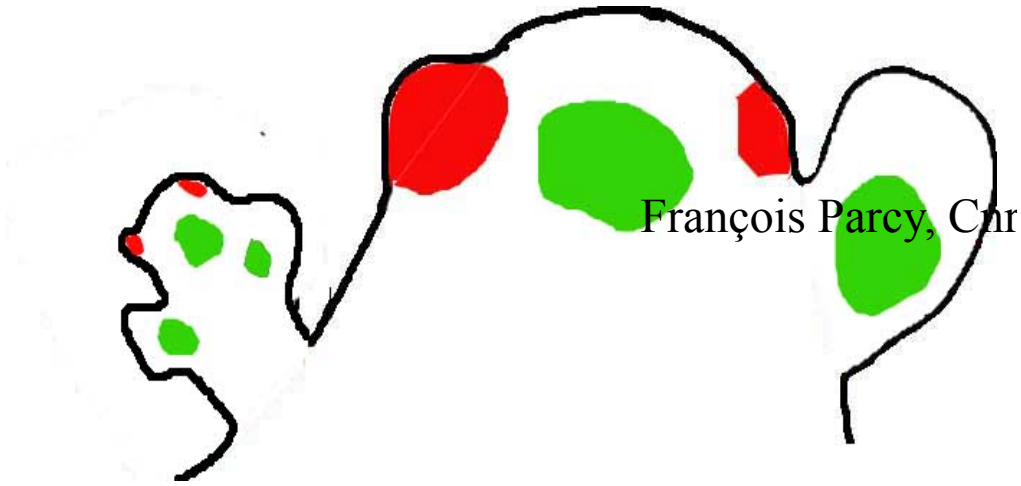
35S::TFL1



lfy mutant

Que se passe-t-il chez *cauliflower ?*

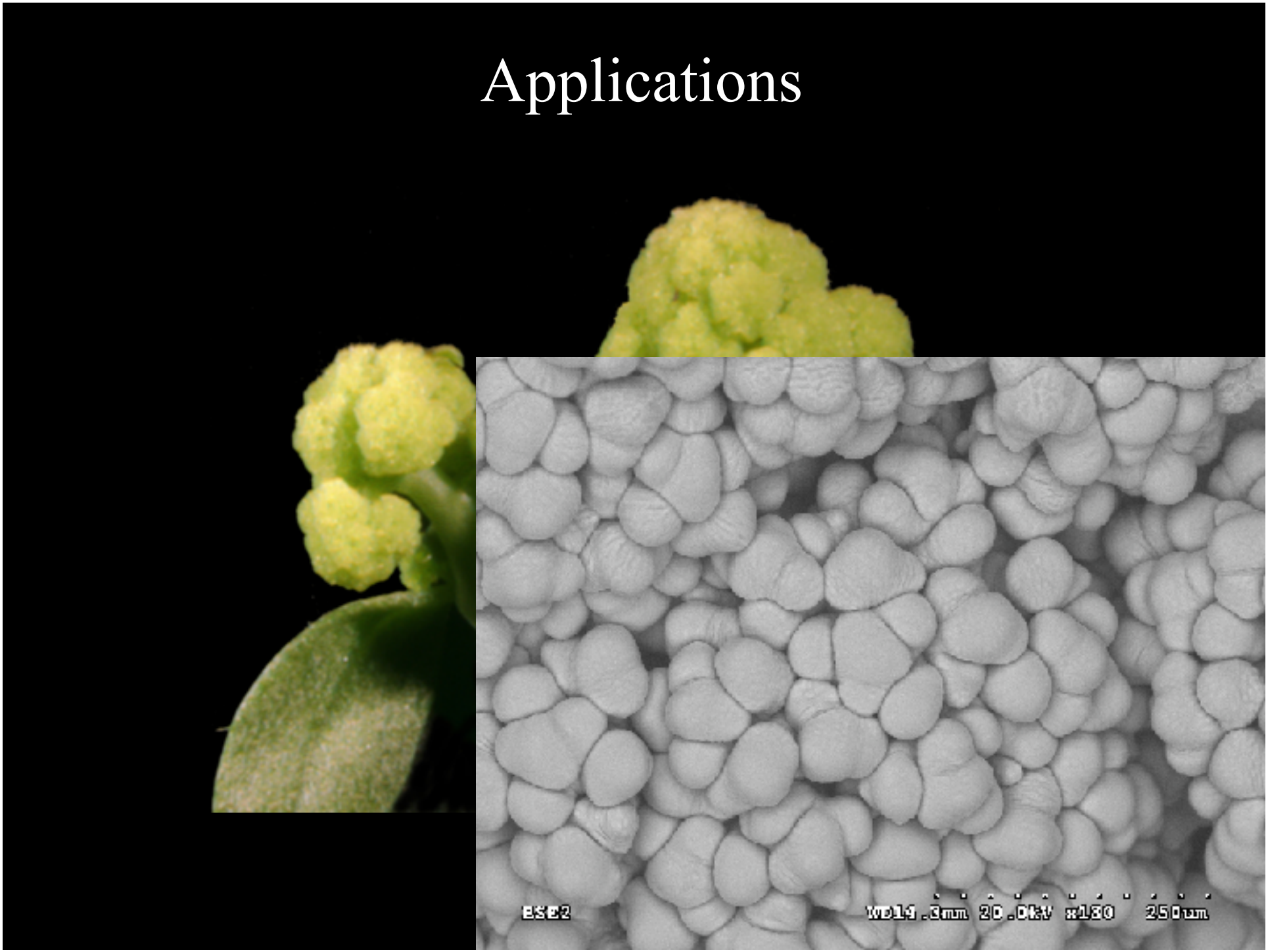




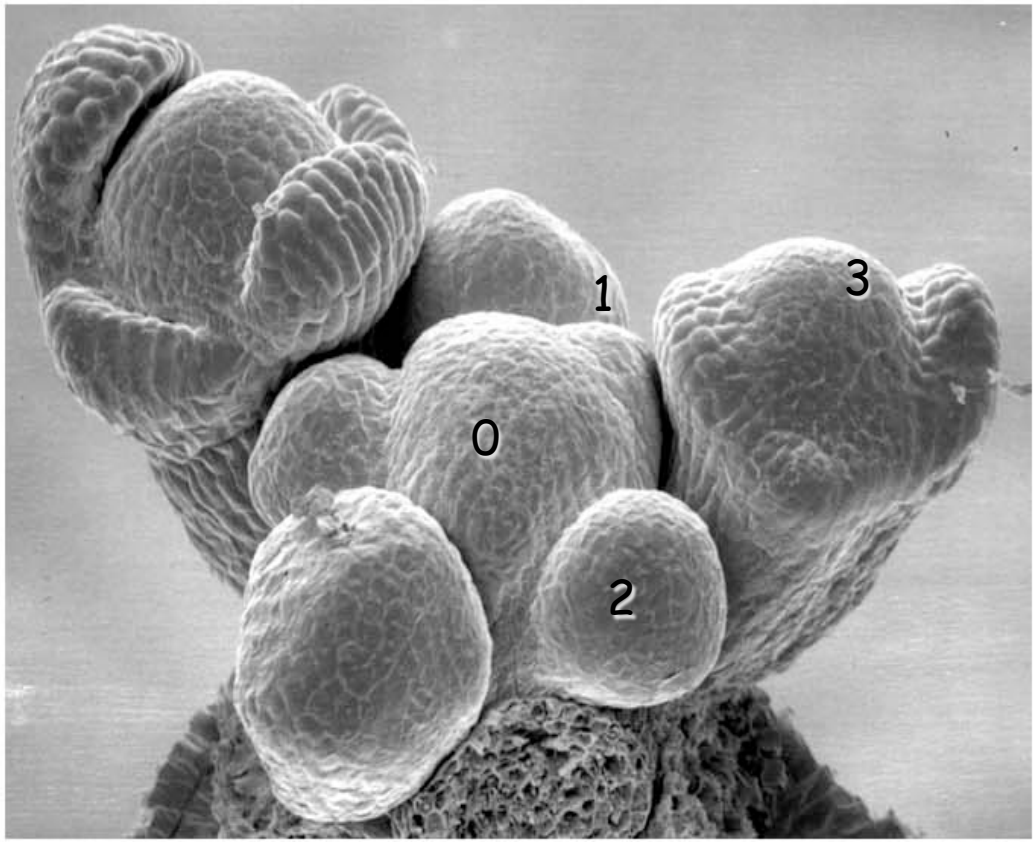
sauvage

mutant *cauliflower*

Applications



Vue de plus près du mutant *cauliflower*



sauvage

mutant *cauliflower*


(a)


A
C